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BULLETIN NO. 17

THE MAGNETITE DEPOSITS OF THE EASTERN MESABI RANGE MINNESOTA

BY
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AND
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The University of Minnesota
1919

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THE MAGNETITE DEPOSITS OF THE EASTERN MESABI RANGE, MINNESOTA

CHAPTER I

INTRODUCTION

LOCATION

The Mesabi range is a belt of iron-bearing formation about 100 miles long, located about 80 miles north of Duluth, which is situated at the west end of Lake Superior. The trend of the belt is east-northeast. (See Figure 1.) The iron-bearing formation, commonly called taconite, is largely drift covered throughout the main range and has few of the topographic features of a "range." It is called a range because iron-bearing formations in other districts form ranges; and at the east end of the Mesabi district there are some rocky hills rising 200 to 400 feet above the general level.

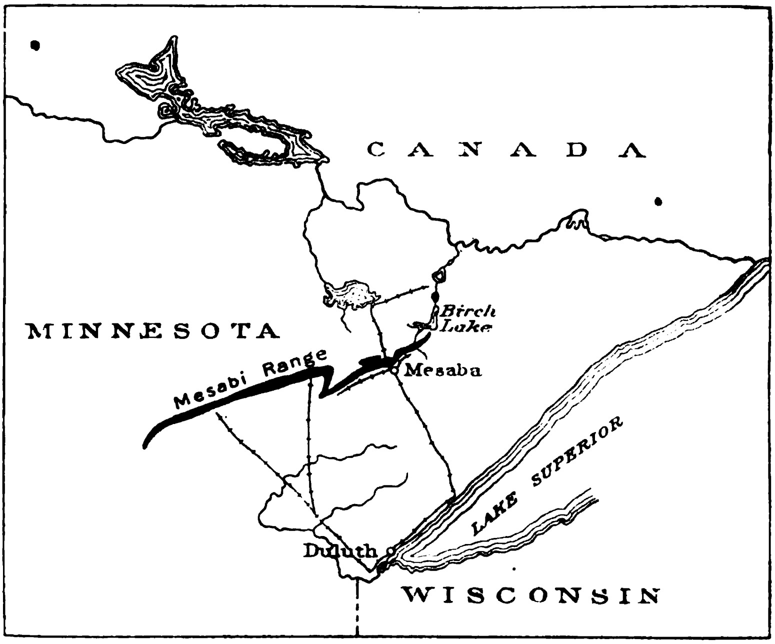


FIGURE 1. SKETCH MAP OF THE WEST END OF LAKE SUPERIOR SHOWING THE LOCATION OF THE EAST MESABI, ON THE MESABI RANGE

This report is a discussion of the eastern end of the range—that part which lies between the town of Mesaba and Birch Lake, a distance of about 20 miles. This portion of the range is commonly called the "east Mesabi." It is distinguished from the rest of the range by several features, besides the topography above mentioned. In this area, outcrops are numerous; most of the iron is in magnetic form; recrystallization has increased the size of grain and reduced the porosity; there has been very little leaching or enrichment; and in places the beds are more highly tilted. These several peculiarities make the east Mesabi a logical unit for separate study.

The field work was done in the summer of 1917, by Frank F. Grout and T. M. Broderick. The Mesabi Syndicate (D. C. Jackling, and Hayden-Stone and Company) were at that time actively exploring certain parts of the area and Mr. W. G. Swart, in charge at the Duluth office, made the work much more effective by rendering many drill records accessible to the Survey. A large number of samples have been assayed in their laboratories.

HISTORY

Leith[1] has summarized the literature of the Mesabi range as a whole up to 1903. It was the magnetite of the east Mesabi that first attracted the attention of explorers. The iron ores are mentioned in a report of 1866.[2] An exploration for iron was made in 1875 and covered very little except the east Mesabi outcrops.[3] All reports indicated that no rich ores were found in large quantities. The later discovery of the richer hematite ores in test pits farther west led to the rush of explorers in 1891 and 1892. Several explorations are reported, both before and after this rush, by N. H. Winchell and H. V. Winchell of the Geological and Natural History Survey of Minnesota.[4] Spurr also prepared a report on the Mesabi iron-bearing rocks.[5] In 1903 Leith issued the monographic report of the United States Geological Survey on the district,[6] and a later monograph on the Lake Superior region includes additional discussions of the Mesabi district.[7] Since the discovery of hematites the east Mesabi has been relatively neglected. Two small hematite mines east of Mesaba have been exploited and for the most part worked out, and no others have been found.

---

[1] Leith, C. K., The Mesabi iron-bearing district of Minnesota: U. S. Geol. Survey Mon. 43, 1903.

[2] Eames, Henry H., The metalliferous region bordering on Lake Superior: First Report of the State Geologist of Minnesota, St. Paul, 1866.

[3] Chester, A. H., The iron region of northern Minnesota: Geol. and Nat. Hist. of Minn. Eleventh Ann. Rept., pp. 154-67, 1884.

[4] See for example, Iron ores of Minnesota: Geol. and Nat. Hist. Survey of Minn. Bull. No. 6 by N. H. Winchell and H. V. Winchell, 1891.

[5] Spurr, J. E., The iron-bearing rocks of the Mesabi range in Minnesota: Geol. and Nat. Hist. Survey of Minn. Bull. 10, 1894.

[6] *Op. cit.*

[7] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior region: U. S. Geol. Survey Mon. 52.

PRESENT EXPLORATION

In the logical continuation of the work of Leith on the Mesabi range published in Monograph 43 and part of Monograph 52 of the United States Geological Survey, it is to be expected that the detailed petrography of the several parts of the iron formation will be the basis of a more detailed stratigraphy. The beginnings of this subdivision of the iron-bearing formation have been made by Leith himself in notes on certain persistent horizons and in maps showing a persistent slate bed. More in detail are the sections worked out by the engineers of the Oliver Iron Mining Company—Kingston, Wolff, Cronk, and others—working under J. U. Sebenius. The sections published by Wolff[8] show numerous persistent beds with recognizable peculiarities.

The east Mesabi is particularly suitable for a study of detailed stratigraphy, because outcrops are vastly more numerous than in other parts of the range, and there are also many drill cores available. The season of 1917 was especially favorable for mapping on account of the recent forest fires and lack of vegetation. It is now thought that the less developed eastern end of the range reveals several recognizable horizons which will aid one to determine the structure and some of the ore reserves in other parts of the range.

The immediate incentive to the study of the east Mesabi was the certainty of magnetite bodies of a large size, and the prospect that they were of a quality and so located as to warrant magnetic concentration. This is a commercial affair and the continued success of such a venture is a matter of close calculation. The costs of several processes involved have been much reduced, and the prices of good low-phosphorus ore are such as to encourage an attempt to mine these ores. In any event, with the reduction of the hematite reserves, interest in the leaner concentrating ore will increase. The details of the occurrence of the magnetite will be of interest in the future, even if present exploration is not continued.

SUMMARY OF THE ORIGIN OF THE MAGNETITE

In a sedimentary rock, such as the taconite, magnetite may accumulate in several ways:

1. By mechanical concentration of magnetite in sand.

2. By deposition as ferric oxide and subsequent alteration to magnetite.

3. By deposition as ferruginous chert in a leaner condition and enrichment to ferric oxide, as ores are now being enriched; and later by alteration to magnetite.

---

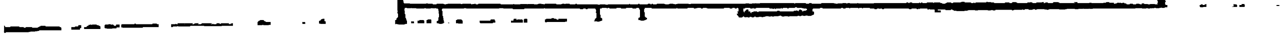
[8] Wolff, J. F., Recent geologic developments on the Mesabi iron range: Amer. Inst. Min. Eng. Trans., vol. 56, p. 148, 1917.

4. By deposition as magnetite from solutions emanating from gabbro or granite near the contact.

The determination of the actual origin, then, involves a determination of the original mineral and textural character; the time the iron oxide accumulated; whether it was enriched, and if so, when; what processes altered the ferric oxides to magnetite; and what igneous rocks contributed to it or altered it. The first drilling that was done ignored the question of origin and only attempted to determine that the known outcrops of ore were connected by similar material under cover, and the depth to which the ore extended. When the matter of origin was considered, a small amount of drilling soon confirmed the observations of outcrops, indicating that (1) the concentration was primary, (2) the original oxides, probably mostly limonite, were altered by general metamorphism to magnetite, (3) none of the igneous rocks have essentially modified the iron content of the taconite, (4) most of the beds showing a concentration of iron are characterized by a conglomerate texture.

PLATE 19

Section of rocks in S.E. ¼ section 6, T. 93 N., R. 13 W., as determined from diamond drill cores



CHAPTER II

GENERAL GEOLOGY OF THE EAST MESABI RANGE

THE FORMATIONS

All the formations of the east Mesabi, as shown in the following table, are in the Algonkian system except the thin Pleistocene deposits. For detailed descriptions of the several formations, reference should be made to the monographs of the United States Geological Survey concerning the region as a whole.[1] Brief notes are given below, but some details are added in the case of the iron formation. The map (in pocket) shows their areal distribution.

Quaternary system	
Pleistocene series	Deposits of late Wisconsin age
Unconformity	
Algonkian system	
Keweenawan series	Duluth gabbro and diabase dikes and sills
Unconformity (only intrusive contacts in this area)	
Huronian series	
Upper Huronian	Virginia slate Biwabik formation (iron-bearing) Pokegama quartzite
Unconformity	
Lower-Middle Huronian	Giants Range granite Slate and schist formation

THE LOWER-MIDDLE HURONIAN SERIES

The slate and schist formation.—These slates and schists are light green rocks of variable grain. Most of them show a nearly vertical cleavage and bedding which strike a little north of east. They include several phases, not very extensive, which apparently represent old intrusions and beds of different character. They extend from the railroad at Mesaba to a point east of the Spring mine in R. 14 W.

The Giants Range granite.—The granite is in general pink, porphyritic, moderately quartzose, hornblende granite. It was intruded north of the present outcrops of green schist and forms the main ridge behind them. The contacts show the intrusive nature of the granite. In much of the east Mesabi the schists were eroded before Upper Huronian time and the iron formation rests on the granite. These contacts do not show any intrusions of granite into the sediments. The granite had evidently been weathered before the sediments were

---

[1] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, 1911.

Leith, C. K., The Mesabi iron-bearing district of Minnesota: U. S. Geol. Survey Mon. 43, 1903.

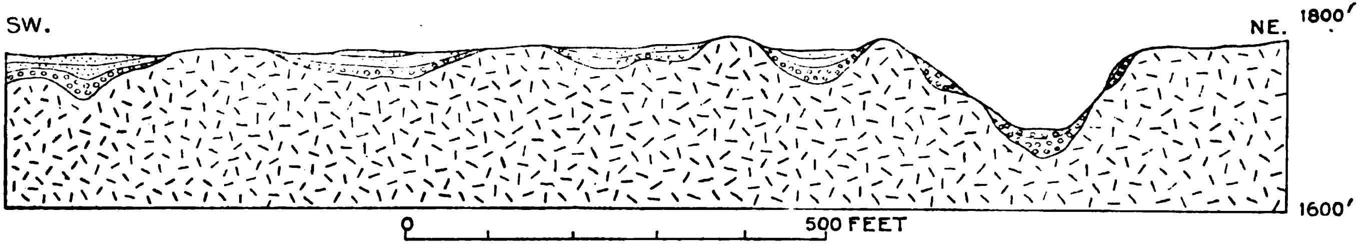
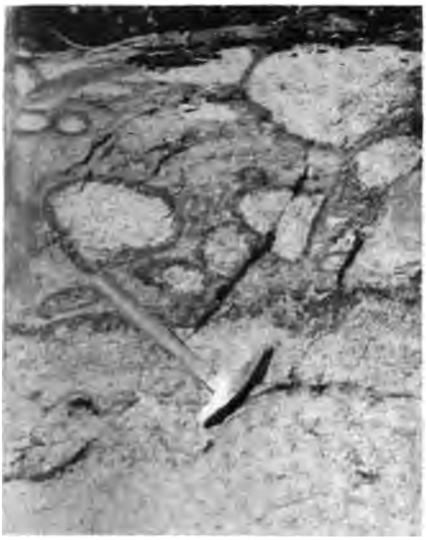
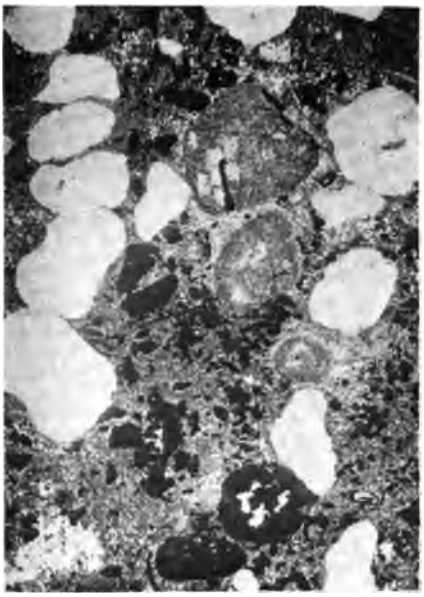


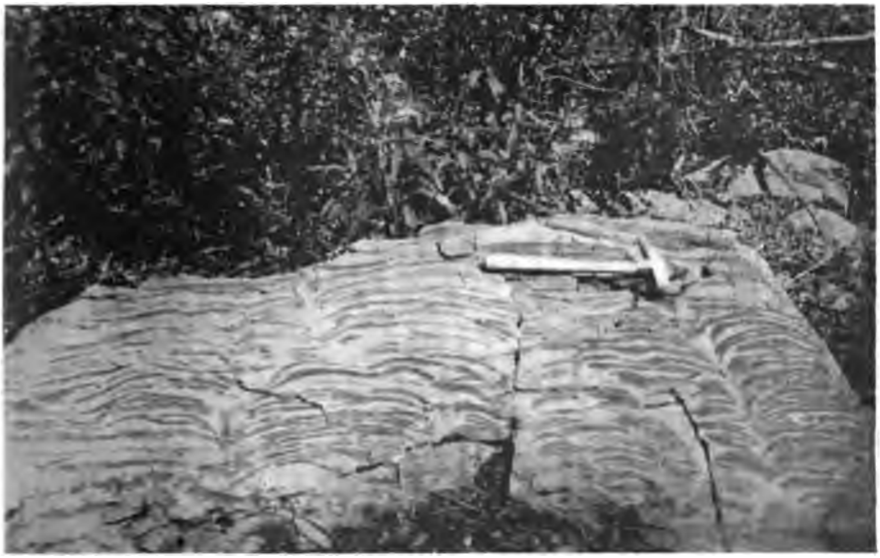
FIGURE 2. A SECTION ALONG THE STRIKE AT THE BASE OF THE IRON FORMATION IN SEC. 17, T. 60 N., R. 12 W., SHOWING THE UNCONFORMITY, AND THE STEEP SLOPES OF THE GRANITE FLOOR



A. THE BASAL CONGLOMERATE OF THE BIWABIK IRON FORMATION, RESTING ON THE GRANITE. THE GRANITE MASS AND BOULDERS SHOW DARK CHLORITIC BORDERS



C. GRANULES OF QUARTZ, MAGNETITE, AND AMPHIBOLE, SIDE BY SIDE IN THE LOWER CHERTY BEDS. MAGNIFIED x 15



B. THE LOWER CHERTY BEDS SHOWING A STRUCTURE LIKE PILES OF INVERTED BOWLS. THIS IS PROBABLY DUE TO ORGANISMS, SUCH AS ALGAE

deposited, for it now shows an upper zone (and a zone around many pebbles in the conglomerate) altered to a quartz-chlorite-garnet rock.

Unconformity.—The erosion preceding the deposition of the Upper Huronian seems to have cut deeply into the slates and granite, and although the general trend of the contact with the over-lying beds is regular, there are minor irregularities indicating a relief of 50 to 100 feet in many valleys in the pre-Animikie surface. Since the sediments are more easily eroded than the basement complex, the present valleys tend to follow, in many cases, the older valleys. (See Figure 2.)

THE UPPER HURONIAN SERIES (Animikie group)

The Pokegama quartzite.—The Upper Huronian (Animikie) formations lie on the older beds with a conspicuous unconformity in most places. The boulders of slate or granite in many places show the derivation from the slate or granite below. Above the coarse conglomerate, and in some cases directly upon the older rock, are finer sediments of several kinds. Where the sediment is quartzite it is given the name of Pokegama as a formation. Where it is cherty and ferruginous it is the Biwabik formation. In many places there is a mixture of clastic grains and a good deal of magnetite, leaving some doubt as to its classification.

The Pokegama quartzite is a hard, pink quartzite in lenses with a maximum thickness of 30 feet in the eastern district. Where it is prominently developed several exposures show a conglomeratic phase at the top. The conglomerate pebbles in most cases are not fragments of the Pokegama, such as would indicate its erosion; but they are chert fragments, probably indicating a breaking up of newly formed sediments above the sand.

The Biwabik iron-bearing formation.—The conglomerate, which is above the granite and schists in most places along the east Mesabi, grades into a series of ferruginous cherty rocks of unusual and variable character. These make a formation 350 to 500 feet thick. Its mineralogy, petrography, and structure are described in detail in later chapters.

The Virginia slate.—The Virginia slate lies with apparent conformity upon the Biwabik iron formation, but the change in material is somewhat abrupt. The cherty ferruginous iron formation may be thin bedded (slaty in texture) in certain parts, but the Virginia slate is slaty in both texture and composition. The contact of the formations is marked by a layer of limey carbonate, rather than a gradation from chert to slate.

The total thickness of the slate can not be measured in the eastern district, for its upper part is everywhere intruded by the Duluth gabbro. The gabbro lies above several hundred feet of slate near Mesaba, but cuts down gradually across the slate into the iron formation near Dunka River, in R. 12 W.

The sills and dikes (*of uncertain age*).—Intruded into the iron formation and the lower part of the Virginia slate are several sills 10 to 20 feet thick. They are much harder than the slate and form conspicuous ridges. Drilling has revealed also several dikes of similar material. The diabase of the sills is characterized by an abundance of coarse white feldspar phenocrysts in most exposures. Each good outcrop shows that the phenocrysts have concentrated in the upper half of the sill. While the sills are mostly fine grained, at many places the phenocrysts are as much as 2 inches in diameter.

The diabase of the sills and dikes would naturally be correlated with the gabbro which is of similar chemical composition, especially since most of the exposures occur at the east end, very close to the great gabbro area. It would be logical to consider them apophyses of the gabbro, except that detailed study shows that they are metamorphosed by contact action of the gabbro. Hence, although they are later than the slate and earlier than the gabbro, it is uncertain whether they were intruded in Upper Huronian or early Keweenawan time. Igneous action was more characteristic of Keweenawan time and in the table of formations given above the intrusions are placed in this division.

KEWEENAWAN SERIES

The Duluth gabbro.—Along the eastern Mesabi practically all of the gabbro is a coarse olivine gabbro with a somewhat variable composition, in alternating bands. The bands dip eastward at a steep, but variable angle. The texture is coarse up to the contact, though in some places the contact is determined only by close study.

CONTACT METAMORPHISM

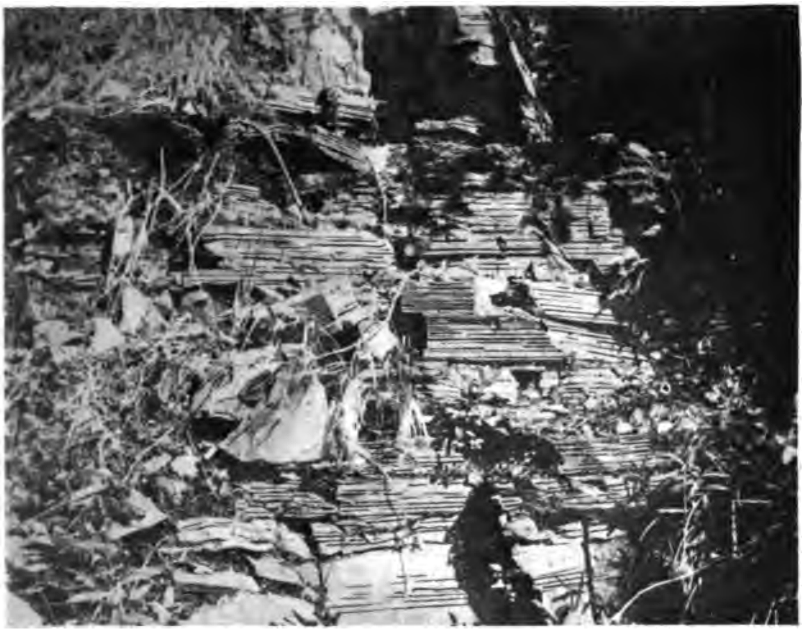
The intrusions of diabase and gabbro have produced alterations in the earlier rocks. The effects of the diabase are not conspicuous except where it is in contact with slates, which are crumpled and recrystallized in a thin zone. The rock is greatly hardened, and spots of cordierite and amphibole appear. A chilled border phase of the diabase is also spotted, containing spherulites, and may be confused with the cordierite rock in the field.

The granite of this area has been described by Leith[1] as intrusive, into the upper Huronian, but it has produced no visible contact effect, and is now believed to be older than the sediments, as it was mapped by Winchell.[2]

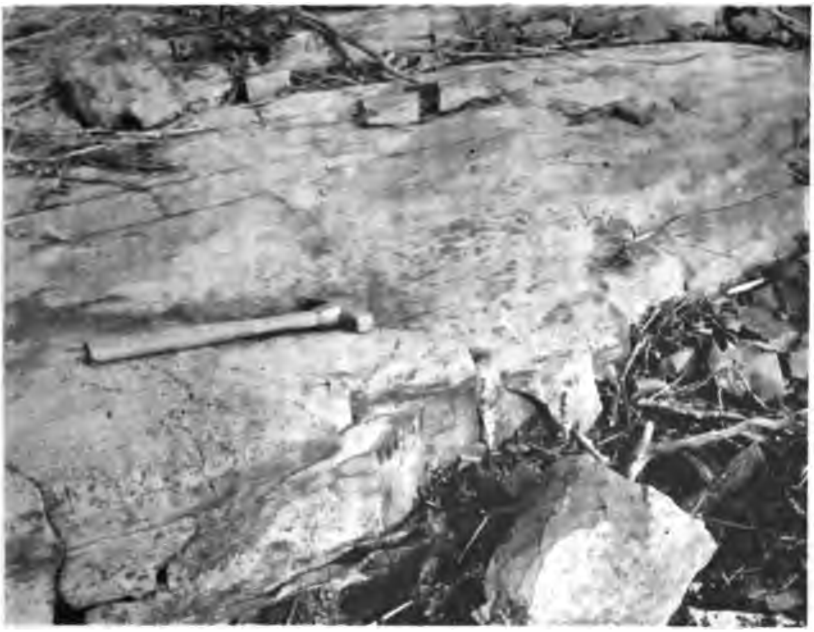
---

[1] Leith, C. K., The Mesabi iron-bearing district of Minnesota: U. S. Geol. Survey Mon. 43, 1903.

[2] Winchell, N. H., Geol. and Nat. Hist. Survey of Minnesota Final Report, vol. 4, plate 67, 1899.



A. THE "INTERMEDIATE" SLATE OF THE BIWABIK FORMATION



B. THE SPOTTED FAYALITE ROCK IN THE SLATY BEDS ABOVE THE INTERMEDIATE SLATE

The gabbro is the largest mass of igneous rock in the region and one of the largest intrusions in the world. The contact effects extend in some places several hundred feet. Probably the most important effect is a very complete recrystallization of practically all the adjacent formations, into a sugary textured hornfels. The weathered surface of the contact rock is at places much like brown sugar in appearance. For this reason, it was referred to as "muscovadite" by Winchell.[4] The uniformity in appearance of the hornfels, whether from slate, diabase, or even from some iron-bearing formation, leads naturally to the conclusion that contributions from the gabbro have considerably changed the composition as well as the texture of the contact rocks. This, however, has not been proved, and the beds are so recrystallized that it is difficult to correlate altered and unaltered beds, if it was desired to make a comparison.

The iron-bearing formation contains bands of quartz and magnetite, which have resisted the apparently general tendency to become hornfels. Recrystallization develops coarse quartz grains up to half an inch thick from chert, amphiboles several inches long from the cherty carbonates, and magnetite in large crystals from pebbles and dust of iron-bearing minerals. It might be expected that iron oxide in the layers would react, during metamorphism, with quartz layers, producing silicates, but there is little evidence of such action. On the other hand, white quartz bands are much more conspicuous than the original gray chert bands alternating with iron oxides, and it is possible that during recrystallization some disseminated magnetite in chert has been more or less segregated into bands. One thin section made from pyroxenite, formed by contact action of the gabbro on the taconite, shows clear evidence of replacement by iron oxide along the borders and cracks. The temperature during recrystallization may have reached 575° C. or more,[5] near the gabbro.

In places, where the gabbro is close to the several horizons of iron formation, pegmatitic stringers are visible in great numbers. The feldspars are coarse and there is a great deal of graphic intergrowth with quartz. Farther away similar patches appear but are less definitely pegmatitic—feldspar is not so prominent, but quartz stringers with vugs are found in similar positions. These stringers are not connected by visible dikes or cracks, but suggest a pervasive emanation from the gabbro. No sign of so much feldspathic material is visible in the less altered iron formation. To check the matter, however, samples were taken from the same horizon near the gabbro and farther away.

---

[4] Winchell, Alexander, Geol. and Nat. Hist. Survey of Minn. Fifteenth Ann. Rept., p. 183, 1886. 'Muscovado" was the early settlers' name for brown sugar.

[5] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 549.

The alkalies were .78 per cent near the gabbro and .38 per cent at a distance. The difference, equivalent to about 3 per cent feldspar, may possibly give a fair idea of the additions of alkalies that took place.

REGIONAL METAMORPHISM

The long time and many events recorded in the geologic history of these formations make it difficult to determine how much of the rock alteration is due to contact action and how much to regional metamorphism. The progressive increase in coarseness of grain toward the gabbro indicates that this coarseness is largely a contact effect. However, the burial of the iron formation under a great thickness of slate favored some general metamorphism. This is shown by the induration and partial recrystallization of the slate itself, and by the drag folds in the less competent beds of the iron formation.

Some of the mineralogical changes in the iron formation seem to vary with the amount of recrystallization and the proximity of the gabbro; others are apparently independent of position and may be attributed to regional metamorphism. For example, it seems unlikely that the original deposit contained iron in a magnetic form, but at present the central beds of the iron formation, where unaffected by weathering, contain about 30 per cent of magnetically separable iron oxides, all the way from the gabbro at the east end of the range, to Coleraine, 60 miles from any gabbro exposures. This may result from a reduction of primary ferric oxides, either by simple heat, by ferrous compounds, or by organic material which is now represented by graphitic beds. There are, in many specimens, intimate mixtures of oxides, which give a red streak but are attracted by an ordinary magnet.

STRUCTURE

The general structure is simple, the beds dipping south and southeast at angles of about 5 degrees, on the side of the great Lake Superior basin. Locally, disturbances such as the gabbro intrusion produced steeper dips. The drag folds, a few feet in extent (Plate XI A) in the thin bedded formation are so placed that they may be related to this larger structure. However, there are folds of intermediate size, one hundred to several hundred feet across. Most of the irregularities shown on the map in the boundaries of the several formations, are due to the valleys crossing gently dipping beds. However, the folds like that at the Spring mine, or south of Iron Lake, are more likely related to some set of forces other than those which produced the major structure, possibly to igneous intrusions or some local modification of the larger stresses by the bed rocks below. The intrusion of the gabbro is very likely responsible for the sharp turn northeast of Dunka River. A few small domes in the lower cherty beds are probably due to the irregularity of the floor on which the beds were deposited.

No faults were noted in the iron formation. If present they are probably of very local significance.

GLACIATION

Throughout a large portion of northeastern Minnesota, glacial ice has scoured off the products of weathering and left relatively thin deposits of gravel. This seems to be true of the east Mesabi range, but on the main part of the range soft hematites have not been entirely removed, and a deeper deposit of drift covers them. The east end of the range stands at a level perhaps 200 feet above the west end, and it is a question whether the absence of soft ores at the east end is due to the fact that they never were formed, or to their formation at a higher level more exposed to glacial scouring, or to a difference in their relation to the lobe of ice that moved across them. Van Hise suggests that some of the range occupies an interlobate position.[6] Many of the rock surfaces are polished and scratched as if considerably glaciated; but in the rock of these high lands there are some gorges cut about 100 feet deep, which have not been obliterated by the glaciation, and it does not seem likely they were formed since glaciation. Possibly the soft ores are absent for the same reason that the rocks stand higher than those farther west; not because of glaciation, but because the rocks were recrystallized, hard, and resistant to weathering.

WEATHERING

The effects of weathering on the iron formation are very slight in the east part of the Mesabi range. The cherts stand out as ridges on the slope below the main granite ridge. The Virginia slate forms a lowland between the gabbro on the south and the granite and iron formation on the north. The slaty layer below the middle of the iron formation is also marked in many places by a valley. These topographic effects are probably due to the more rapid weathering of the slate.

In exposed places the cherty iron ore has stood under the weather probably for centuries without apparent attack. On the other hand, ground waters of different kinds produce some effects. The leaching of silica at the hematite mines has probably resulted from alkaline solutions which might originate near the granite. Contrasted with this, the swamp waters are acid and any taconite in the water loses its iron minerals; magnetite and fayalite dissolve rapidly, amphiboles next, and quartz remains. Most of the springs issuing from the iron formation and the waters reached in drilling, are almost free from iron. In swampy areas there are some limonite deposits. A spring carrying considerable iron issues in sec. 27, T. 60 N., R. 13 W.

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[6] Van Hise, C. R., Iron-ore deposits of the Lake Superior region: U. S. Geol. Survey Twenty-first Ann. Rept., pt. 3, pp. 411-12.

CHAPTER III

THE MATERIAL OF THE IRON-BEARING FORMATION

MINERALS OF THE IRON-BEARING FORMATION

The following minerals have been noted in the iron formation of the east Mesabi.

Quartz is the most abundant mineral in the recrystallized taconite. It occurs also in fragmental grains and a few small veins and septaria cracks. Chert and jasper make up some large primary beds, two of which show structures indicating organic (probably algal) origin. Some of the cherts and jasper layers were broken into fragments and pebbles.

Amphibole is the second mineral in abundance in the main taconite beds. It was probably formed by metamorphism of the greenalite and other silicates, that may have been present in the primary deposit. It is now intergrown with the quartz and magnetite. Rounded markings, consisting of amphibole in quartz, are seen in some thin sections—apparently the only remaining sign of an original granule texture. Some conspicuous grains, poikilitically enclosing quartz, etc., have grown to be 6 inches or more in length. Dark amphiboles are conspicuous also in pegmatitic stringers near Dunka River. Most of the amphibole is light green, and may be classed as actinolite, but other specimens vary from yellow to black. Grünerite and cummingtonite have been reported. The darker silicate in many specimens is probably grünerite.

Magnetite forms variable layers almost pure, up to 6 inches or more thick, alternating with the more common intergrowth of quartz, amphibole, and magnetite. Magnetite occurs also as pebbles, small rounded granules, crystals, and most commonly intergrown with quartz and amphibole, making up small rounded granules, and the matrix of the granules. There is a slight concentration of magnetite in a zone at the border of many granules. Recrystallization is so complete that little trace of granules is visible except these rings of fine grained magnetite. No attempt has been made to distinguish magnetite from other magnetic iron oxides. Ordinarily it is probably correct to call a magnetic oxide with a black streak, magnetite. In some parts of the Mesabi range there may be other magnetic oxides.

Hematite and *limonite* were rarely seen in the east half of the area except as a slight film of weathered mineral. At several places in the western part the leaching and oxidation have produced considerable bodies of these ores. In much of the western belt, the fresh black magnetic ores also show in places a red streak. The hematite and magnetite are intimately mixed, and magnetic concentration separates most of the iron oxides from the silicates.

Garnet is developed at several horizons in the iron formation. In the chloritic alteration product of the weathered granite and conglomerate at the base of the formation are many small, well formed red crystals. A more massive brown garnet forms layers and spots with the amphiboles, etc., near the slaty beds of the formation. While garnets may be found at a number of horizons, the only other prominent occurrence is above the main conglomerate beds; here also it is brown and in irregular spots.

Fayalite is conspicuous in crystals up to an inch in diameter. Most of them are about the size of peas. The fayalite is yellow when fresh, and brown when weathered. Thin sections show that most grains have thousands of microscopic inclusions of quartz and amphibole. Some have also magnetite. Fayalite was seen in greatest abundance in the slaty taconite above the main slate of the iron formation, and was best developed in R. 12 W.

Pyroxenes include augite, diopside, and hypersthene. The augite forms metacrysts resembling fayalite, in the recrystallized cherty taconite. Hypersthene was seen only in pegmatitic stringers near Dunka River. Babingtonite has been reported.

Mica occurs as microscopic grains in the altered slaty horizons. A larger specimen was seen in a drill core from the taconite near Sulphur.

Feldspars are not seen in the main outcrops, but both orthoclase and plagioclase occur in the pebbles of granite in the basal conglomerate; also in the pegmatitic stringers near the gabbro.

Carbonates are to be found in small amounts in the ore horizons intergrown with quartz, amphibole, and magnetite. A layer rich in calcium and possibly other carbonates is more or less continuous at the upper contact of the iron formation, and some carbonate appears in the lean taconite, just below this layer,—Aub_6. The magnetite-rich bed below the intermediate slate also contains carbonate. Secondary carbonates have been deposited in openings in the leached zones, where there has been enrichment, and in pseudomorphs after some of the granular greenalite.

Greenalite has been found mostly in the more western parts of the area. Nearer the gabbro, recrystallization has altered it to several other minerals, and more or less modified the texture of the rock, so that little greenalite is left. We have checked the low alkali content of greenalite rock by several analyses. The granules of amphibole may form from greenalite with little change in material.

Graphite.—Many black layers and flint concretions and pebbles in the midst of magnetite-quartz masses prove to contain little or no iron. The solution of the silica and iron by successive treatments with hydrofluoric and hydrochloric acids leaves a soft black residue, apparently graphite.

Apatite is not visible in most thin sections, but has been detected in the coarser recrystallized ore at the east end of the Mesabi range.

Chlorite is characteristic of the basal conglomerate where the feldspars were weathered before metamorphism. Some is believed to occur also in the aluminous beds higher in the formation.

Pyrite occurs as numerous scattered small bunches below the slate member of the iron formation, and is scattered in small amounts at other horizons.

Pyrrhotite, *chalcopyrite*, and *arsenopyrite* have been noted in drill cores.

Epidote and *tourmaline* are visible in the contact zone near the gabbro.

Kaolin may be present in some of the slates.

Malachite is derived from chalcopyrite near the surface.

ROCKS OF THE IRON-BEARING FORMATION

It has become the custom on the Mesabi range to refer to practically any phase of iron formation (except hematite ore and paint rock) as taconite. Most of the rocks are derived from an original sediment containing granules that may have been greenalite, but the greenalite is so altered in most specimens that the name greenalite-rock is applicable to very few. There are, of course, small amounts of some ordinary sediments, conglomerates, quartzite, and slate, with the usual range of impurities, but these make up a very small proportion of the whole. From the prominence of fine quartz, the rocks may properly be classed as cherts, with various qualifications to distinguish the minerals intergrown with the quartz; thus there are ferruginous cherts, amphibolitic cherts, calcareous cherts, and sideritic cherts. These so-called cherts, however, differ considerably in origin from the concretionary and precipitated cherts of limestones and common sediments. They are derived by alteration from the rocks with granules like those of greenalite. Furthermore, in certain places, there are, in the iron formation, chert concretions of a more normal sort, and it is somewhat confusing to make no distinction. For the rocks of the east Mesabi there are several reasons why the name *chert* is not very satisfactory. The granules, analogous to the greenalite structures farther west, vary in size up to pebbles 6 inches in diameter. Recrystallization has enlarged the grains so that many specimens no longer have any resemblance to common chert. For these reasons we use the local name, taconite, in its broader sense for any part of the iron formation. Certain phases may be easily classified as chert, amphibolite, pyroxenite, quartzite, amphibole-magnetite rock, or magnetite; others have so many rare minerals or such unusual proportions of minerals that no name has been given and a descriptive name becomes very cumbersome. Added to this, it may be necessary to use a textural qualification. There are, for example, some cherty amphibolites with fayalite metacrysts; and some conglomeratic augite-amphibole-quartz-magnetite rocks. Probably no elaborate additions to the nomenclature are desirable, and the general term taconite may be understood to cover these recrystallized rocks.

CHAPTER IV

SUBDIVISIONS OF THE IRON-BEARING FORMATION

The several divisions of the iron-bearing formation here tabulated (Plate III) are based to a large extent on the appearance of outcrops. Wolff[1] has emphasized the fact that the several grades of Mesabi ore are more or less related to the beds from which they were formed; and this relation is even more pronounced in the magnetite than in the hematite ore. The divisions previously made by Wolff are indicated

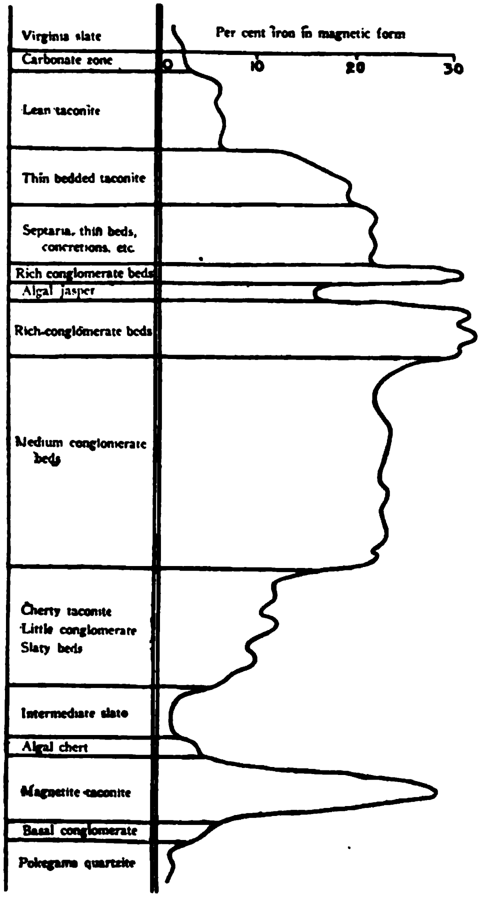

FIGURE 3. CURVE SHOWING THE VARIATION IN MAGNETIC IRON CONTENT IN THE SEVERAL HORIZONS OF THE IRON FORMATION ON THE EAST MESABI

in the diagrammatic sections (Figure 4), and were useful in the structural studies on the east Mesabi: but the thickness of the main divisions is very different in this part of the range from those plotted by Wolff. Some of the divisions are given detailed descriptions on pages 19 to 26.

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[1] Wolff, J. F., *op. cit.*

Tabular Section of the Biwabik Formation Where Prospected for Iron on the Eastern Mesabi

Top	VIRGINIA SLATE	
	UPPER SLATY BEDS	
Aub$_6$	Limy carbonate layers. Less than 5 per cent magnetite.....	5 to 10 feet
	Banded amphibole and white quartz in thin layers up to 6 inches thick. Less than 5 per cent magnetite..........	40 to 50
Aub$_5$	Taconite in thin beds mostly less than ⅛ inch thick. About 20 per cent iron in magnetite, decreasing at the top....	25 to 35
	Taconite in thin beds, like above, but alternating with thicker gray beds and concretions with a granule texture, and white quartz septaria. The thin beds are drag folded and even brecciated. A zone of garnets occurs near the bottom. About 20 per cent iron in magnetite......	40 to 45
	UPPER CHERTY BEDS	
Aub$_4$	Dark heavy taconite, with some conglomerate texture, and granules, alternating in thick beds with thick magnetite layers. About 30 per cent iron in magnetite..........	10
	Jasper and chert with algal structure and conglomerate. About 15 per cent iron in magnetite..................	1 to 10
	Dark heavy taconite like the bed above the jasper. About 30 per cent iron in magnetite........................	20 to 30
	Gray taconite with conglomerate and granule texture and many thinner lenticular beds of magnetite. About 20 per cent iron in magnetite.........................	80 to 110
	LOWER SLATY BEDS	
Aub$_3$	Fine massive to slaty quartz amphibolite with only obscure granule structure, and few magnetite beds. Fayalite crystals in places. About 10 per cent iron in magnetite.	65
Aub$_2$	Black thin bedded slate, more or less recrystallized. About 5 per cent iron in magnetite........................	25
	LOWER CHERTY BEDS	
Aub$_1$	White to gray chert with coarse algal structures. Less than 5 per cent iron in magnetite....................	10 to 15
	Variable taconite with some cherts, breccias, fragmental sands, garnets, etc. From 25 to 35 per cent iron in magnetite	2 to 52
	Basal beds; conglomerate in many places, and (in absence of Pokegama quartzite) some green shales. Less than 5 per cent iron in magnetite........................	0 to 15
		350 to 470
Base	GIANTS RANGE GRANITE; OR LOWER-MIDDLE HURONIAN SLATE; OR POKEGAMA QUARTZITE.	

LOWER CHERTY BEDS

The bottom of the lower cherty beds, Aub_1, is for the most part a conglomerate of irregular thickness, which fills in some of the erosion valleys in the older surface. It is not separately shown on the map. Where it rests on granite, as it does in most of the east Mesabi, some of the boulders are clearly of the same granite. Evidently the weathering of the boulders and the granite below left an aggregate which under later metamorphism developed chlorite and garnet, between the original quartz grains that seem to remain unaffected (Plate III A). Between the pebbles and in thin beds overlying them are greenish shaly beds, probably derived from the same weathered granite. Where the iron formation rests upon the older slates or the Pokegama quartzite, this basal bed consists mainly of quartz and chert pebbles.

Above these basal beds is the lowest of the magnetite beds. It is not recognized at the east end of the area, but is found a few feet thick in R. 13 W., and over 50 feet thick near Mesaba. It contains magnetite layers more or less mixed with sand and cherts. (See Plate III C.) There are phases that resemble the conglomerate of the upper cherty beds, but more that seem to be brecciated after deposition.

The increase in thickness toward Mesaba and the high per cent of iron make this bed of interest as a prospective ore horizon farther west. It is no doubt the bed which Wolff describes as producing "hard blue ore" in the "brown cherty taconite."[2] Toward the east where it is thin it was missed in so many places that it has not been mapped as a continuous belt.

At the top of the lower cherty beds, a hard chert crops out in many places, indicating a continuous formation over the length of the range. Most of the rock is of fine grain and has a peculiar structure, emphasized in gray and white or jaspery bands. (See Plate III B.) The bed is not so lenticular and irregular as the concretionary beds, such as occur above the slate, but is characterized by a more regular waviness, probably due to organic action. It closely resembles several forms from the pre-Cambrian ascribed to algal growth. Similar forms were recently described and illustrated by Moore from the iron formations near Hudson's Bay.[3] These forms on the Mesabi are almost wholly chert, while the others are characteristically calcareous. Nevertheless they are considered of organic origin, for it is likely that many early forms of chert are analogous to later calcareous forms.[4] The concentric masses are 6 to 18 inches across. (See also the description of smaller algal forms in the upper cherty beds, page 22.) The gray color of some bands may be due to their magnetite content, but only a few thin layers in the cherts have a high per cent of iron. In some outcrops the banded cherts include fragments of iron oxide, so that the rock greatly resembles the conglomerate beds of the higher divisions of the formation. The thickness of these lean beds below the slate is about 15 feet and is fairly constant in the eastern area.

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[2] *Op. cit.*, p. 154.

[3] Moore, E. S., The iron formation on Belcher Islands: Jour. of Geology, vol. 26, pp. 425-26, 1918.

[4] See Clarke, F. W., Geochemical evidence as to early forms of life: Jour. Wash. Acad. Sci., vol. 6, p. 603, 1916.

LOWER SLATY BEDS

The lower part of the lower slaty beds, Aub_2, is the most notably slaty in structure of any part of the iron formation. It is known through the main range as the "intermediate slate." (See Plate IV A.) In contrast with the lower beds it is very constant in thickness and bedding through the whole range. It is probable that the lower beds had filled up the irregularities in the bed rock surface before the time of deposition of the slate. It is so much more like an ordinary shale that it is natural to attribute the material to normal mechanical deposition and, in contrast, to attribute the ferruginous cherts to precipitation. Well-developed ripple marks are seen in places. None of these slaty beds contains much magnetite. Extensive recrystallization at the east end does not prevent the weathering to thin slabs along the bedding, at most outcrops. An analysis of the slate by George Steiger is reported by Van Hise and Leith.[1]

This bed grades into overlying rock of a very different general character, with no sharp break. The slates, about 25 feet above the bottom of the bed, become more granular in texture and show less regular bedding. Higher up the rocks are hard and fine grained, with conchoidal fracture. They are more massive in structure as compared with the thin beds below. Thin sections show a mat of very fine amphibole needles in chert, with a very obscure granule structure. In a few places small areas of conglomeratic texture appear, with small magnetite pebbles, but abundant magnetite is found in few beds, and as a whole, in very small amounts. In the area near Sulphur the rocks of this division show fayalite in many outcrops. Plate IV B shows the spots that develop as the fayalite weathers brown. As a division of the formation it will be called the siliceous bed above the intermediate slate.

UPPER CHERTY BEDS

The lower part of the upper cherty beds is the lowest bed with a thickness as much as 50 feet that contains a large per cent of magnetite. The line between this bed and the more siliceous beds below is not sharp, but the formation in a few feet becomes granular, magnetite pebbles grow more numerous, and layers of pure magnetite become thicker and more abundant. The whole mass is characterized by the occurrence of the pebbles. No exposure 5 feet thick lacks pebbles. Any drill core from these beds that is 5 feet long will show cross sections of pebbles.

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[1] *Op. cit.*, p. 191.

A vertical section of the bedding shows it to be very irregular. Most of the beds, whether of magnetite, conglomerate, or amphibole, pinch out in irregular lenses. Such a bedding is illustrated in Plate V A. It is not regular enough for ripple marks; neither is it evidently related to folding; both ripples and folding are observed in the beds independently of this structure. There are no signs of cross bedding. Three processes are suggested below (in discussing the origin of the magnetite deposits), which may have made the beds irregular: (1) the shrinkage of a colloidal precipitate; (2) the solution of deposited layers: and (3) concretionary rearrangement.

Many of the pebbles of the conglomerate are of magnetite, many are of material resembling the beds just below, and many show a core of siliceous granular rock with a zone of magnetite around the border. Plate V B indicates the variety of pebbles in a fair sample. The shapes are mostly somewhat flattened and fairly well rounded, but a considerable number are angular, and plate-like. Some vertical sections of the beds indicate that magnetite layers, which can be traced some distance, may be broken up into flat, vertical-sided blocks at one end. (See Plate V A and Plate VI A.)

The matrix between the pebbles in the lower part of this bed is much the same as the main portion of the bed under it; but in the middle and upper parts, it is of sandy or granule texture, containing much more magnetite, and showing under the microscope structures that have been attributed to greenalite. In the altered grains of these rocks, there seems to be no difference in the nature of the material in the granules and in the coarser pebbles. Grains of the same general character range in size from $\frac{1}{16}$ inch up to 6 inches. There is no break in the series. (See Plate IX.)

The magnetite content of these beds is fairly constant if taken in large masses. However, it is possible to select five-foot drill cores, or five-foot exposures, a few feet apart along the beds, which will vary as much as 50 per cent of the total. This is exceptional and the average magnetic iron[6] content is probably well above 20 per cent. Total iron is about 37.5 per cent.

The next division of the upper cherty beds is not essentially different from the main conglomerate, except that the magnetite layers

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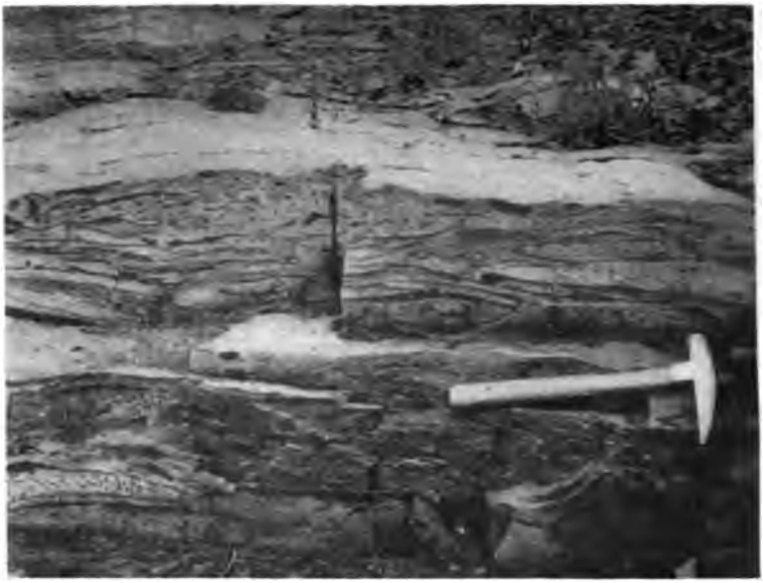
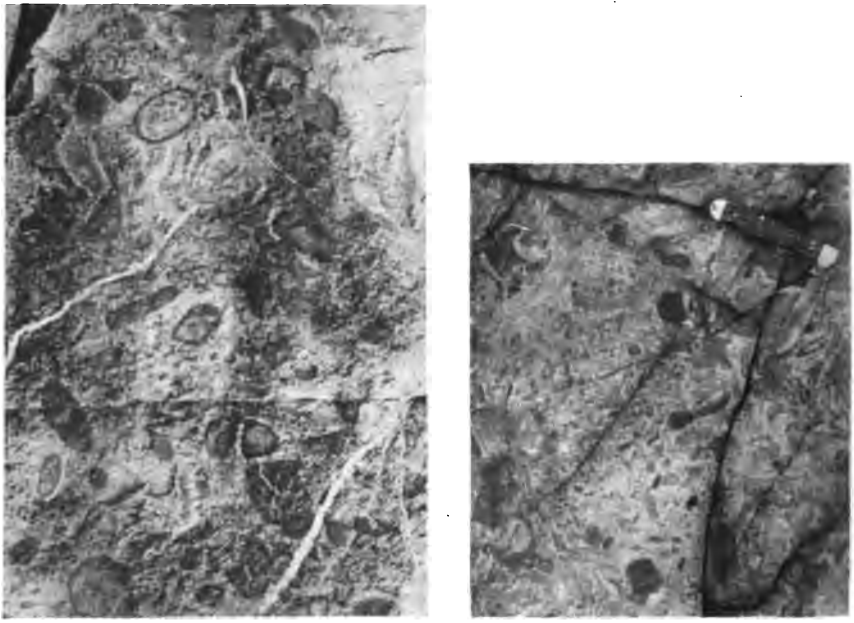
[6] The term "magnetic iron" is used in this report to designate the iron contained in minerals which are attracted by an ordinary hand magnet.

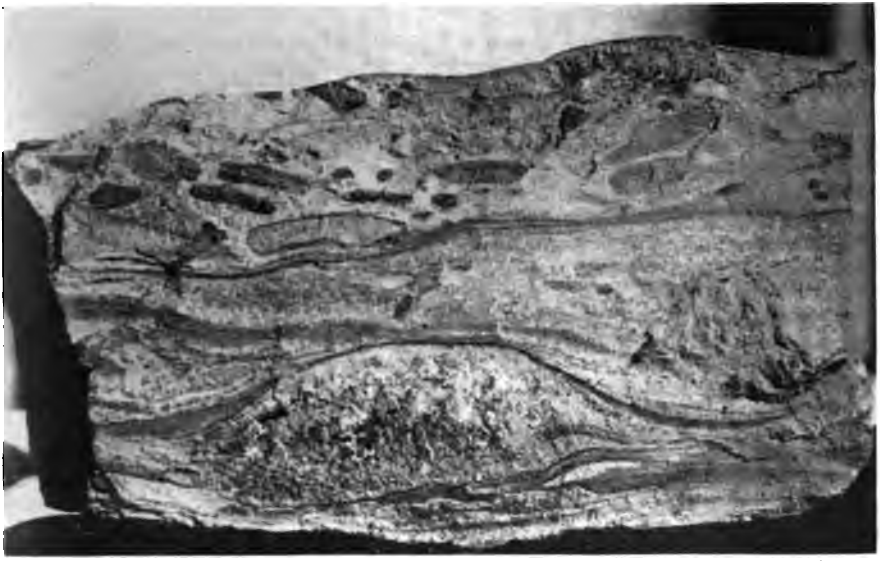
PLATE V



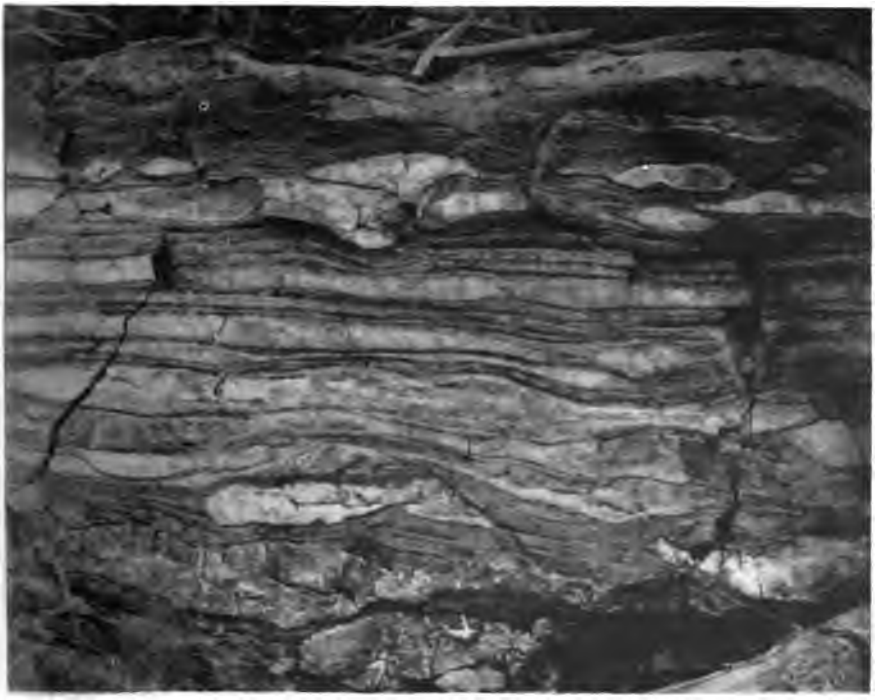
A. THE CHERTY TACONITE OF THE MAIN MAGNETITE BEDS ON THE EAST MESABI, SHOWING THE LENTICULAR BEDS, WITH SOME INDICATIONS THAT THE BEDS BREAK UP INTO CONGLOMERATE PEBBLES



B. TWO CLOSE VIEWS OF THE CONGLOMERATE



A. CHERTY TACONITE SPECIMEN SHOWING THE IRREGULAR BEDDING AND THE PARALLELISM OF THE FLAT PEBBLES OF THE CONGLOMERATE



B. THE UPPER SLATY BEDS, SHOWING SOME NODULES OF COARSER CHERTY MATERIAL, GRADING INTO LENTICULAR BEDS OF SIMILAR MATERIAL

are thicker and more numerous. This seems to be the best magnetite deposit as much as 20 feet in thickness. To the west of this area the richer beds show a red streak indicating considerable hematite, though magnetic concentration separates most of the iron.

Above the best magnetite deposit is a thin bed of cherty or jaspery material with the characteristic algal structure mentioned in the description of the upper part of the lower cherty beds. This bed is very hard, and so placed in the midst of hard beds that it outcrops in many places. However, it is too thin to show on the map. The color varies from gray to red, with variation in composition, but the cause of the variation is undetermined. The magnetite content of the algal bodies is slight (see Plate VII), but between the finger-like masses are some pebbles of magnetite and granular material much like the conglomerates in adjacent beds.

The bodies whose origin is here attributed to algal growth resemble little piles of thimbles or inverted bowls. They are half an inch to three fourths of an inch in diameter, piled in irregular columns about six to twelve inches high. The lower parts, like the sides and upper parts, seem to merge into the granular fragmental material of the conglomerate. Along the east Mesabi the curving lines of the structure do not seem to include any fragmental grains or granule markings except along the margins. However, some drill cores from taconite near Eveleth show a more confused mixture of banded jasper and pebbles, indicating that the growth could occur simultaneously with fragmental deposition and even concentrically around the grains. Horizontal sections of these masses show the concentric rings of a concretion, but the vertical sections are not easily explained as concretionary, or even as results of diffusion. It seems more likely that the finger-like masses grew, convex surfaces upward, all over the bottom of the water. Plate VII shows the characteristic forms. It is noteworthy that these small growths, forming a layer a few inches thick, are so widespread that the structure serves as a horizon marker in the drill cores examined from places all along the range. The outcrops indicate a continuous bed 15 miles long and the curving bands are so small that they are easily recognized in drill cores far to the west of the outcrops.

Specimens of the algal material were examined by Dr. Charles D. Walcott, who writes; "I am still at a loss to explain the origin of such structure without the influence of some organic agency acting in conjunction with diffusion and concretionary phenomena. The structure is very much like that which occurs in the siliceous limestones of the pre-Cambrian in the Grand Canyon, Arizona, and somewhat like those found in the pre-Cambrian Belt series of Montana. The Grand

Canyon forms are referred to Collenia."[7] No cell structures have been detected in the thin sections of this rock, but recrystallization has been so complete that it probably destroyed all trace of algal cells, which are less than .01 mm. across. The forms may safely be attributed to probable algae.

The top of the upper cherty beds is in nearly every respect a continuation of the best magnetite bed, below the chert layer. It seems that the algal growth occurred at one stage in the accumulation of the conglomeratic ore. Possibly the accumulation never ceased, for the spaces between the algal "fingers" are filled with similar pebbly material.

All this rock that has as much as 25 per cent magnetic iron can be concentrated to a product over 60 per cent iron, without grinding finer than about 100 mesh. The thin sections show a large proportion of the magnetite to be recrystallized grains of large size, and easily separated from the silica.

Summarizing, it may be said that the upper cherty beds, with the exception of the algal chert near the top, constitute a unit in which the subdivisions are more or less arbitrary. The total thickness is between 120 and 160 feet with a little richer material near the top. The conglomerate is most conspicuous in R. 12 W. and is a distinguishing feature throughout the entire thickness of the upper cherty beds. While the thickness of these beds with relatively high magnetite content apparently remains about constant throughout the entire Mesabi range, the conspicuously conglomeratic phases, containing within them the best concentrations of magnetite, may be thinner toward the west.

UPPER SLATY BEDS

The lowest of the upper slaty beds marks the end of most of the coarse conglomerate. There is no abrupt change, however. The granule texture is seen in lenses in the slaty beds and there are even a few pebbles. Two features distinguish these beds from the preceding: first, the magnetite layers instead of being lenticular and compact, are straight thin layers of very fine grain, a set of thin magnetite beds alternating with the lenticular beds of granule texture; second, the coarser beds contain and may consist of nodules, or concretions distinct from the matrix. Plate VI B shows these two features and indicates clearly the characteristic nodules.

The development of nodules has probably played a more or less prominent part in the history of the formation. The nodules are not recognizable in drill cores, but they are very clear in the exposures and grade into the lenticular bedding, so as to suggest

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[7] Walcott, Chas. D., Pre-Cambrian Algonkian algal flora: Smithsonian Miscellaneous Collections, vol. 64, no. 2, p. 111, 1914.

that the very lenticular beds, even in the conglomerate, may have developed by concretionary action. It is noteworthy also that the nodules and matrix have the granules and even pebbles in them; so that the growth of a nodule apparently does not mean a replacement of all the material by a uniform precipitate from solution; rather it must have been more like a special cementation of a certain part of the beds.

One of the most striking features noted in the outcrops of taconite on the east Mesabi is the septaria cracks in these beds. Septaria seem to have been described chiefly in carbonate concretions; and there may have been more or less carbonate in the iron formation—some still is to be found. The concretions now, however, are mainly quartz and magnetite, while the cracks are filled with white quartz. Plate VIII shows the appearance of the septaria. They are very useful in determining the horizon of an outcrop.

Several of the magnetite beds of this division have been crumpled or drag folded between more competent layers of chert, and more or less irregularly thickened (Plate XI A).

There are abundant brown spots of garnet near the bottom of this bed, as compared with other parts of the magnetite rocks, but the garnet zone is too thin to be separately mapped.

The abundance of thin magnetite beds makes the average of this bed worthy of consideration, though its concretions have only a small amount, and the finer grain requires finer grinding for good concentration. The magnetite bands, under the microscope, show swarms of minute quartz and amphibole inclusions and intergrowths, and Mr. E. W. Davis of the Mesabi Syndicate found that grinding must be carried to about 300 mesh to get a concentrate over 60 per cent iron.

On the basis of the thin beds of fine grain, we have correlated these beds with Wolff's "upper slaty" beds, since he states that his terms are textural only and do not refer to composition. This report refers to them as "septaria beds."

The beds above the septaria beds are similar in most respects, but septaria cracks have not been noted. They have less of the concretionary forms and granule structure, but the thin beds with a fair per cent of magnetite persist, growing a little leaner at the top. This upper part is not separated from the septaria bed in the general map. It has a relatively small number of magnetite layers, and grades into the beds above, (Aub$_6$).

Taken together, the beds mapped as Aub$_5$, are about 75 feet thick, except east of the Dunka River where they seem to be thinner. The outcrops show very little slaty character, except that the magnetite layers are very thin. Near Spring mine there is an outcrop at this

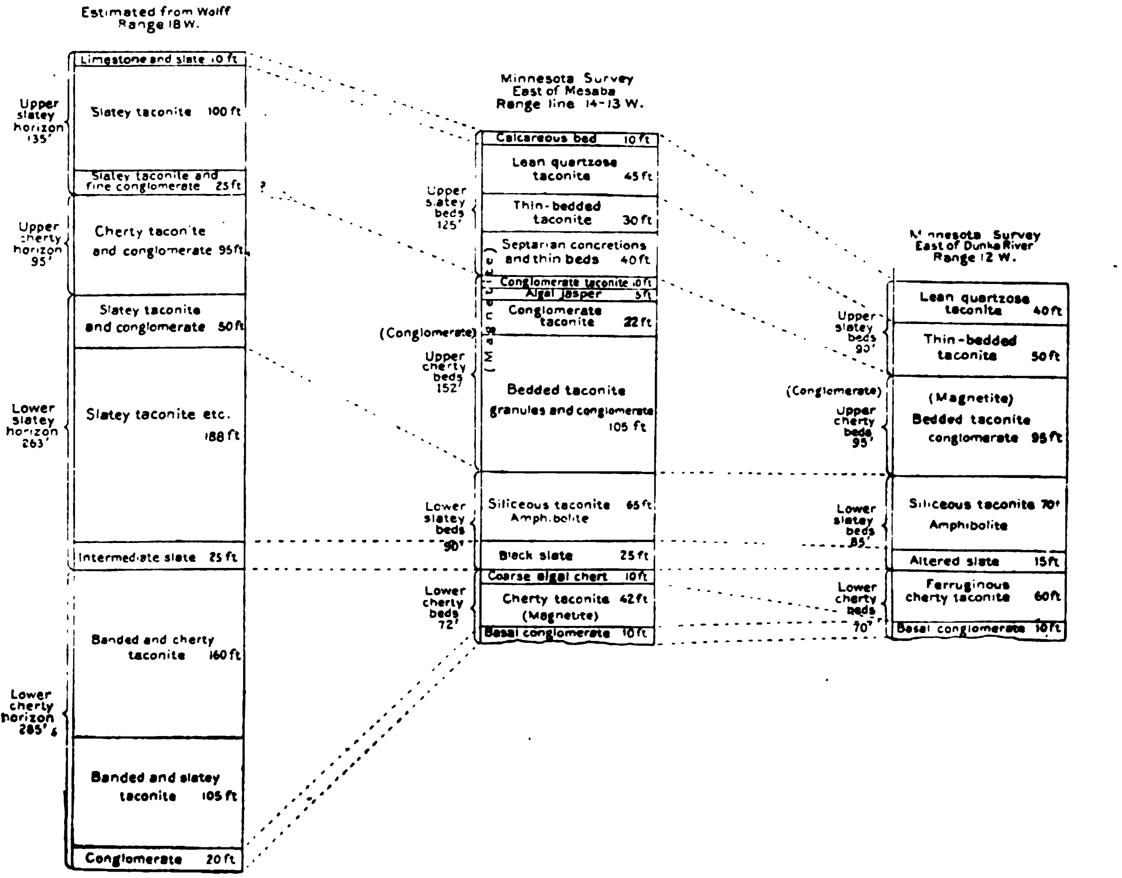
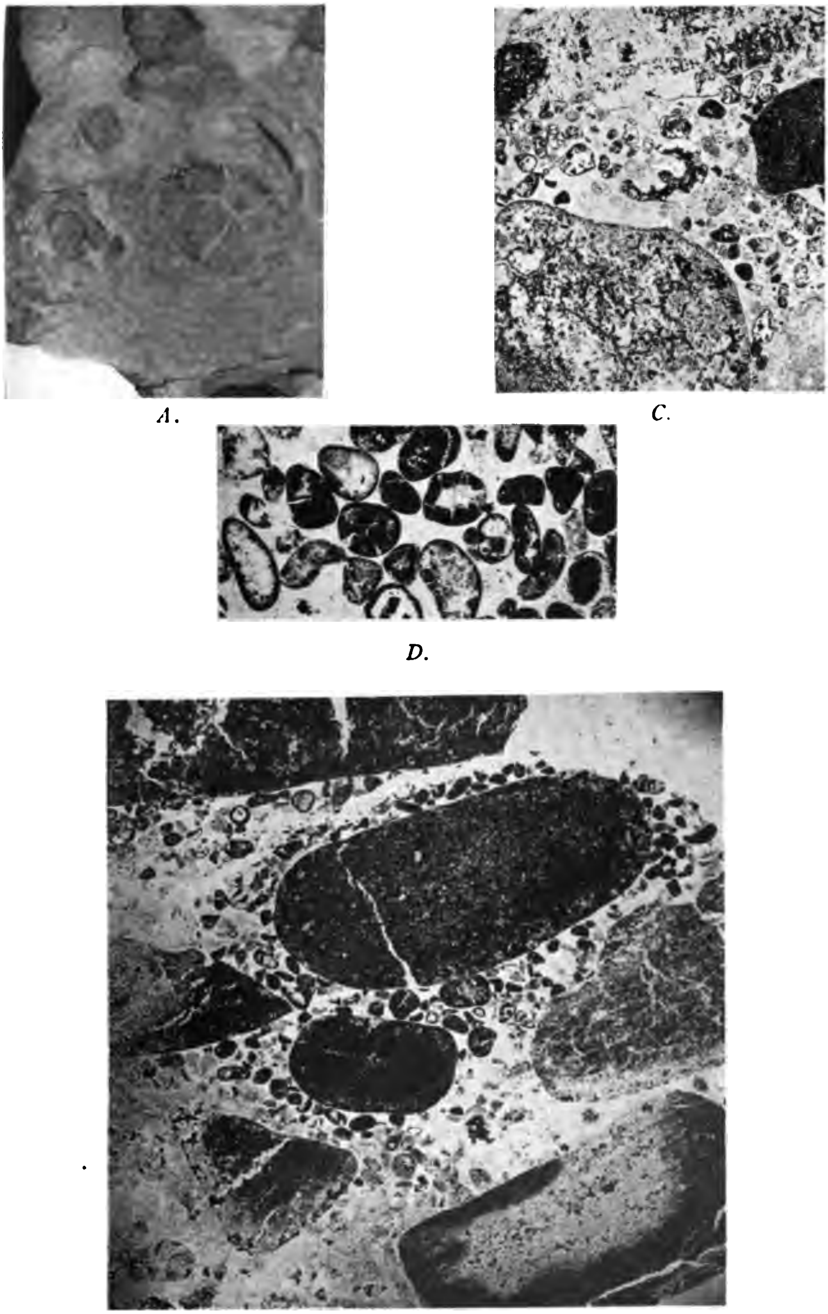

Estimated from Wolff Range 18 W.
Limestone and slate 10 ft
Slatey taconite 100 ft
Slatey taconite and fine conglomerate 25 ft
Cherty taconite and conglomerate 95 ft
Slatey taconite and conglomerate 50 ft
Slatey taconite etc. 188 ft
Intermediate slate 25 ft
Banded and cherty taconite 160 ft
Banded and slatey taconite 105 ft
Conglomerate 20 ft
Upper slatey horizon 135'
Upper cherty horizon 95'
Lower slatey horizon 263'
Lower cherty horizon 285'
?
Minnesota Survey East of Mesaba Range line 14-13 W.
Calcareous bed 10 ft
Lean quartzose taconite 45 ft
Thin-bedded taconite 30 ft
Septarian concretions and thin beds 40 ft
Conglomerate taconite 10 ft
Algal jasper 5 ft
Conglomerate taconite 22 ft
Bedded taconite granules and conglomerate 105 ft
(Magnetite)
Siliceous taconite 65 ft Amphibolite
Black slate 25 ft
Coarse algal chert 10 ft
Cherty taconite 42 ft (Magnetite)
Basal conglomerate 10 ft
Upper slatey beds 125'
(Conglomerate)
Upper cherty beds 152'
Lower slatey beds 90'
Lower cherty beds 72'
Minnesota Survey East of Dunka River Range 12 W.
Lean quartzose taconite 40 ft
Thin-bedded taconite 50 ft
(Magnetite) Bedded taconite conglomerate 95 ft
Siliceous taconite 70' Amphibolite
Altered slate 15 ft
Ferruginous cherty taconite 60 ft
Basal conglomerate 10 ft
Upper slatey beds 90'
(Conglomerate)
Upper cherty beds 95'
Lower slatey beds 85'
Lower cherty beds 70'

FIGURE 4. CORRELATION CHART OF THE BIWABIK IRON FORMATION FROM CENTER TO THE

PLATE IX



A.

C.

D.

B.

A, *B*, *C*, AND *D*. A SERIES OF GRAINS FROM 0.1 MM. TO 30 MM. SHOWING SIMILAR FORMS, COMPOSITION, AND DETAILED STRUCTURES. *A*. PEBBLE AN INCH IN DIAMETER. *B*. MAGNIFICATION x 8 ½, GRAINS FROM .1 MM. TO 10 MM. *C*. THE SAME. *D*. COMMON GRANULES ABOUT 1 MM. OR LESS.

horizon that weathers into thin slabs and breaks up much more readily than most of the taconite.

The upper member of the formation lies on the slaty beds just described, with a rather sharp change in character. The magnetite is almost entirely lacking and the thin beds and granule texture have not been noted. Beds of white quartz and green silicates, from half an inch to 6 inches in thickness alternate to make a conspicuously banded light colored rock. Scattered grains of carbonate are more abundant than in the lower beds. There is little reason for describing this division as slaty, but it lies between slaty taconite and Virginia slate, and is not given a separate group name. It is everywhere about 50 feet thick.

The topmost bed of iron formation does not outcrop at many places and is too thin to show on the map. It is a calcareous bed about 10 feet thick. Nearly every drill core that passes from Virginia slate to iron formation reaches such a bed just below the slate. This is not a pure limestone, but is more calcareous than any other beds of the iron formation. It is generally assumed that this marks the top of the iron formation. In contrast with the varying character of the iron formation, the slate above is very uniform, so that this last change in material is a good horizon to select as the upper limit of the formation.

CORRELATION OF SEDIMENTS OF EAST AND WEST MESABI

The section given differs in some details from the sections given by Wolff, but there seem to be sufficient data for the correlation given in Figure 4. The persistent and characteristic "intermediate" slate is so well identified that it may be at once correlated with the slate in the eastern area. From this correlation it follows that the beds below the slate are much thinner at the east than on the main part of the range. Wolff shows the lower cherty beds about 280 feet thick; at Mesaba they are about 70 feet and in R. 12 W., about 30 feet thick. Accompanying this change, and agreeing well with it, the Pokegama quartzite disappears to the east. It is clear that active sedimentation began somewhat later in the east Mesabi than farther west.

The persistence of the layer of calcium carbonate at the top of a series of four recognizable divisions of the iron formation is taken as a very strong indication that all the iron formation is represented in this eastern section. Van Hise and Leith[8] refer to the "known irregular alternation of iron-bearing formation and slate, both across and along the beds," as a cause of the varying width of the iron-bearing formation. However, where the exposures are best and drill cores most numerous, there is no alternation that causes any doubt as to the location of the limiting zone of carbonate. The reduction in thickness and width of outcrop is not explained by a lateral gradation of the upper beds into slate. Wolff, in calling attention to the variation in thickness in neighboring drill holes, suggests an erosion after the deposition of the iron formation was completed, but the persistence of the upper beds makes this less likely than the variation in thickness of the lower beds.

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[8] *Op. cit.*, p. 174.

Thus the reduction in the total thickness of the iron formation from 800 feet, as a large average, to 400 feet at the east, is largely attributable to the thinness or absence of the lower beds. The granite surface on which the iron formation was deposited, in R. 12 W., shows valleys about 80 feet deep. The upper beds, however, decrease somewhat in thickness.

The value of such correlation has been emphasized by Wolff in his work on the hematite ores.[9] In summary it is found that the character of the hematite, whether blue and hard, or brownish-yellow and soft, is largely determined by the original horizon. Leith has noted a very constant relation also between the amount of phosphorus and the horizon;[10] the finer grained rocks, slate and paint rock, and the ores near them have high phosphorus. It is noted by both Leith and Wolff that the detail of differences in beds, and the correlation of beds, can be used to determine structures in the iron formation; and the slumping and folding so determined are guides to the occurrence of leached and enriched ore.

Wolff observes further that the lower cherty and upper cherty horizons seem to be the most susceptible to enrichment into ores. Emphasis should be placed on this fact here, for it is not an accidental or arbitrary condition. The original taconite was richer in these horizons. It is evidently more likely that ore will be enriched to 55 per cent iron, if the original contained 30 per cent, than if it had less than 10 per cent iron. On the east Mesabi, interest centers in the quality of the original, unenriched taconite, and since the several beds are characteristically rich or lean this determination may guide the exploration farther west along the favorable horizons.

Plate X shows that the several horizons are recognizable in drill cores and can thus be traced across the range.

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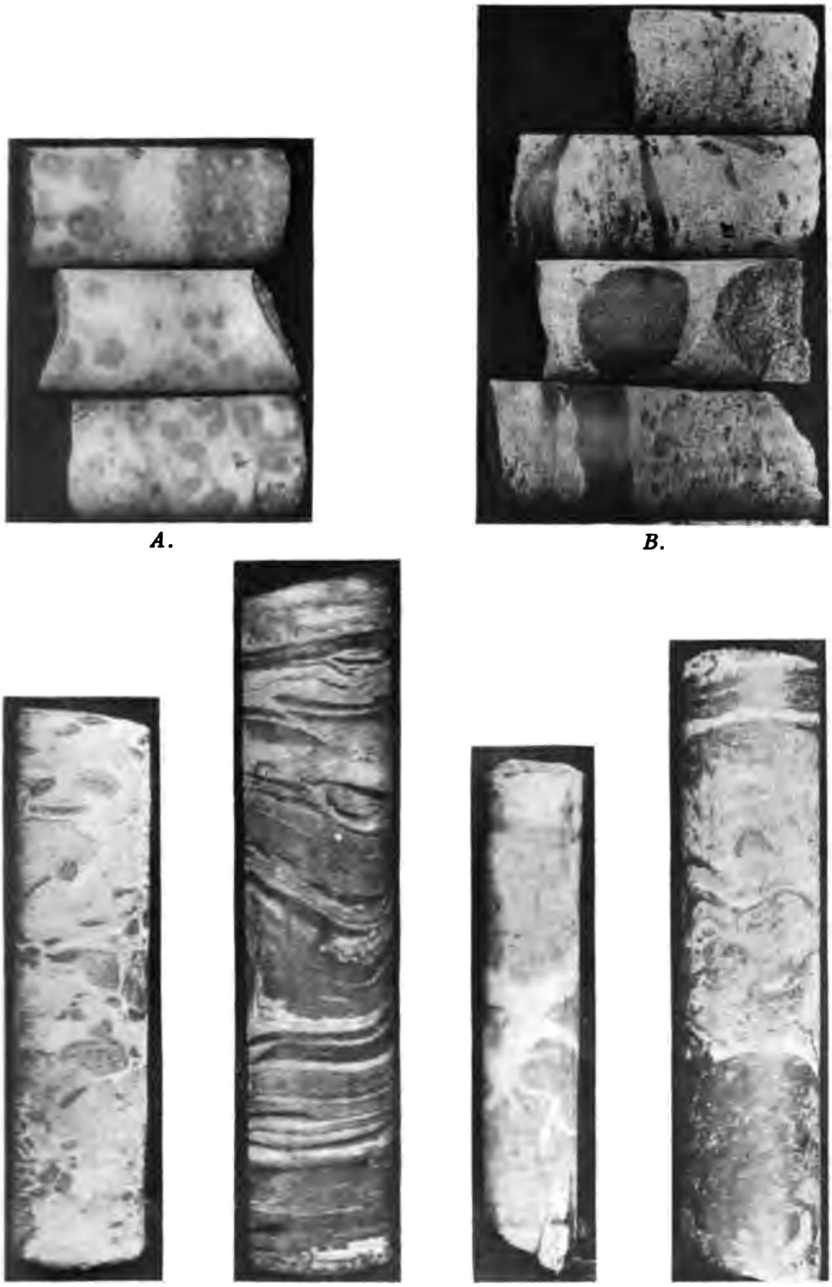
[9] *Op. cit.*, p. 154.

[10] Leith, C. K.. The Mesabi iron-bearing district of Minnesota: U. S. Geol. Survey Mon. 43, 1903.

PLATE X



A. B.

B C. D. E.

DRILL CORES SHOWING THE SEVERAL HORIZONS RECOGNIZED AS CLEARLY AS IN THE OUTCROPS. *A*. LOWER SLATY BEDS WITH FAYALITE. *B*. CONGLOMERATE. *C*. UPPER SLATY BEDS DRAG FOLDED. *D*. SEPTARIA CRACKS. *E*. ALGAL CHERT

CHAPTER V

THE HEMATITE ORE DEPOSITS

The Graham pits at Mesaba.—The two Graham open pits at Mesaba are near the main line of the Duluth and Iron Range Railway. They were until recently worked for hematite. The magnetite which may be assumed to have been the chief primary iron mineral is almost wholly oxidized in the workable ore. Very little attention is given in this paper to the process of enrichment of such ores. It is noteworthy, however, that the horizon of the ore bodies is shown to be that of the primary magnetite beds (Aub_4 and Aub_5). Septarian flint concretions occur near the tops of the pits.

The Mayas mine.—The enriched hematite of the Mayas mine was apparently about worked out to the depth of the pit. Some ore is left in the bottom, as shown by recent drilling. The hematite concentration at this point occurred near the horizon of the lower zone of magnetite concentration below the intermediate slate. Recently the demand for manganese has led to renewed exploration of the pit and several layers with 6 to 30 per cent manganese have been uncovered and mined. These are to be attributed to secondary concentration.

The Spring mine.—The ore of the Spring mine, like that at the Mayas mine, was concentrated at the horizon of the lower magnetite bed, below the slate. Oxidation has not been complete in all parts of the ore, as the remnants left in the pit contain considerable magnetite. The ore formerly mined, probably all of the best grade, may have been mostly oxidized.

Hematite prospects.—Prospects and drill holes show hematite at several places east of the Spring mine, but all show a mixture of hematite with magnetite. None seem to have been rich enough to warrant development. Most of the prospect holes are in the lower magnetite zone, below the slate. An area in the N.W.¼ sec. 28, T. 59 N., R. 14 W., received special attention.

The enrichment of hematite ores.—The leaching, oxidation, and enrichment of these ores was no doubt accomplished by the processes affecting the ores farther west, and studied in detail by Leith[1] and Wolff,[2] both of whom recognize a relation of the enrichment to folds and jointing. The eastern hematite deposits have not been examined in detail, but it is noteworthy that the Spring mine, the most easterly mine worked, is in a rather sharp fold. It may also be noted that the lower ore horizon is near the granite, and likely to receive alkaline solutions that would leach out silica; while the upper ore horizon along much of the belt is nearer to a swampy tract where the acid water would dissolve out iron rather than leave the ore enriched in iron.

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[1] Leith, C. K., The Mesabi iron-bearing district of Minnesota: U. S. Geol. Survey Mon. 43, 1903.
[2] Wolff, J. F., *op. cit.*

It is commonly supposed that the enrichment of the soft hematites of the Mesabi occurs without much effect on the state of oxidation of the iron. However, it is clear that at these eastern mines the iron of the fresh taconite was mostly in magnetic form. Outcrops on both sides of the hematite body contain magnetite. Since this magnetite has been altered to the ferric iron producing the secondary hematite ore bodies, it is possible that magnetite may have been the chief primary oxide all along the range. This is indicated by some preliminary tests on drill cores from the central and western parts of the range.

CHAPTER VI

THE MAGNETITE DEPOSITS—GENERAL

The minerals of the deposits.—Practically all the minerals mentioned as occurring in the iron formation, are found in the magnetite bodies. Probably over 95 per cent of the beds Aub_4 and Aub_5 consists of amphibole, quartz, and magnetite. To the west, some hematite is intergrown with the magnetic iron oxide.

The magnetite is rarely pure, but the impurities are the intergrown quartz and amphibole. There are very small amounts of pyrite, and analyses show that the phosphorus is low in the beds containing the most magnetite. Titanium has not been found even in the deposits close to the Duluth gabbro, which contains much titaniferous magnetite.

Chemical composition of the magnetite rock.—Van Hise and Leith[1] give the following analysis of the average rock of the east Mesabi (apparently the samples are actually from the Gunflint Lake region) which is tabulated, for comparison, beside the average taconite of the west Mesabi.

Average Composition of Amphibole-Magnetite Rock and Taconite of the Mesabi District

	Amphibole-Magnetite	Taconite
SiO_2	60.51	58.71
Al_2O_3	1.20	.54
Fe	25.22	25.71
MgO	.52	.....
CaO	.67	.....
H_2O	Small	(Ignition) 1.96
P_2O_5	.05	(P) .021
S	.59	
MnO_2	.92	
TiO_2	None	

As compared with these analyses, which represent the average of the whole formation, the following results were obtained by J. H. McCarthy, at the Minnesota School of Mines experiment station, on an average sample taken from the upper cherty beds, where magnetite is more abundant than in the average of the whole formation.

Analysis of an Average Sample of Cherty Beds of Magnetite Rock near Sulphur

SiO_2	45.17
Al_2O_3	0.67
Total Fe	33.80
CaO	3.02
MgO	2.39
CO_2	0.58
TiO_2	Trace
Mn	0.61
Soluble Fe	29.20
P	0.049

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[1] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, pp. 181, 185, 204.

Textures.—The textures of the magnetite and its matrix are probably indicative of their origin. The most conspicuous features are the abundance of conglomerate in the upper cherty beds and the concretionary beds above the conglomerate. (Plates V B and VI B.)

The granule texture of the taconite in layers alternating with magnetite has been studied in detail by Leith, who ascribes most of it to the occurrence of greenalite in the fresh original rocks. In the altered rocks of the main eastern area, greenalite is entirely recrystallized. Some granules of amphibole may represent original greenalite, but there are many rocks in which the texture gives an impression of a series of fragmental grains of varying size. The small grains are less than .05 inch, but they seem to have similar characters in all sizes up to 6 inches. Most of the grains are magnetite in large part, though the magnetite may be intergrown with or intimately related to the quartz and amphibole. Many of the pebbles are cherts or other siliceous material. Many of the siliceous pebbles have a richer magnetite rim or border. A few are zoned in alternating bands of magnetite and siliceous matter, as if altered by diffusion. Many are fractured in an irregular network of cracks resembling septaria, with white quartz filling. These remarks apply to the microscopic grains as well as to the larger pebbles. (See Plate IX.) Some of the larger pebbles consist of conglomerate made of granules and smaller pebbles.

Some of the black pebbles show a dull appearance resembling graphitic rather than ferruginous minerals. Many of these have adjacent to them in the granular matrix a zone of lighter color than the average matrix. Some of the pebbles, themselves composed of granular material, are hardly distinguished from their granular matrix.

The magnetite layers alternating with the conglomerate and granular taconite are compact and contain more or less quartz and amphibole intimately mixed. Many of them, however, seem fairly pure.

The concretions, bearing septaria of white quartz, have been described above as guides to horizons near the center of the magnetite deposits.

All these textures tend to become obliterated by recrystallization, northeast of Dunka River. The conglomerate, however, is recognizable almost to Birch Lake, while the chert becomes an aggregate of quartz with grains up to half an inch in diameter. The coarser grain has an economic significance, because in the magnetic separation the grains of impurities must be separated by the grinding, and the coarser ores require less grinding to give a clean concentrate. It is probable also that the reduction in porosity during crystallization, from 5 per cent to less than 1 per cent,[2] is responsible for the lack of much weathering in the eastern areas.

Stratigraphy of the magnetite.—It has been found that the amounts of magnetite in the several beds of the iron formation here distinguished are fairly constant over a wide range of territory. The preliminary estimates made on field observations have been checked by a number of assays, and notwithstanding considerable local variation in any given bed, the concentrations of iron prove to be at fairly uniform horizons. Figure 3 gives a generalized estimate of the horizons of magnetite concentration. It may be assumed at once that any large area of the conglomerate bed and probably the lower member of the upper slaty beds will bear about 20 per cent of iron in magnetically separable form wherever they are located east of Mesaba, except in the rare case of weathering to hematite. In detail, however, these beds in large areas probably vary from 12 to 28 per cent in magnetic iron. Drilling has already shown some variations, and there are concealed areas as large as a square mile. Furthermore it may be assumed that the smaller beds just above and below the cherty beds with algal structure, will be considerably richer than 20 per cent iron in magnetite. In the magnetite beds, the iron in minerals other than magnetite increases the total iron content to about 35 per cent, but this is not considered available, so long as the recovery of iron depends on magnetic concentration. The smaller magnetite layer below the intermediate slate is perhaps less uniform, and certainly not exposed in so many places, but it is similar in grade to the thicker upper zone.

The importance of the detailed stratigraphy reported in Chapter IV becomes apparent as soon as the deposits of magnetite of this grade prove to have commercial value. Outcrops along the range are about as numerous in one horizon as another, and the identification of any one horizon will be a definite guide to the location of the magnetite deposits. The persistence of certain features such as the algal structure and septaria cracks, or even the intruded diabase sills, makes it possible to determine the limits of the magnetite zone with unusual accuracy even without drilling. A small amount of drilling confirms the field estimates in most cases. The drill cores furnish still other horizon markers. Mr. Fred Jordan, one of the engineers conducting the explorations near Sulphur, has found that correlation is possible on the basis of the per cent of soluble iron in the tailings from magnetic concentration. This iron may be in the form of fayalite or siderite, or possibly hematite. The fayalite was most often noted in the field.

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[2] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 554.

It is to be expected from the greater thickness of the iron formation farther west, that there will be some variation in the thickness of magnetite zones. The irregularities of the bedding, on a small scale, might suggest that the deposit would be erratic. Nevertheless it may again be emphasized that in spite of local variation the average magnetite content of certain beds is high enough to be of interest. The thickness of the main zone carrying conglomerate or septaria is 200 feet, and as this increases to the west, there may be included lean beds. A certain amount of drilling is necessary to determine the favorable locations. Outcrops and drill records, however, in R. 12 W., show a conglomerate zone 100 feet thick near the center of the iron formation. Wolff shows a similar section with conglomerates through a zone of 100 feet in R. 18 W., and 95 feet in R. 20 W., 35 miles west of the eastern Mesabi area. These records make correlation fairly safe.

Distribution of the magnetite deposits.—The magnetites east of Mesaba were known before the deposits of the Mesabi range west of Mesaba were developed. The changes from hematite ore bodies under drift, farther west, to harder magnetite in good exposures farther east, are conspicuous. Certainly the proportion of hematite in the formation grows rapidly lower to the east of Mesaba. Nevertheless when attention is directed to the leaner, unaltered taconite containing magnetite, and the secondary concentrations are ignored, the amount of ferruginous material that can be concentrated magnetically from fresh taconite is only slightly less near Mesaba than farther east. West of Mesaba fresh taconite, mostly from drill cores, is available from Aurora, Gilbert, Virginia, Eveleth, Hibbing, and Coleraine. Concentration tests on these samples indicate about as much magnetic iron in these cores as there is in the area between Mesaba and Birch Lake. The data at hand indicate that the horizons of primary iron concentration (now magnetic) are probably just as thick as they are east of Mesaba. The western areas are more interrupted by secondary leached zones of hematite, and are much more deeply covered with drift, but there can be no doubt that large bodies of lean taconite in the western areas carry over 20 per cent iron in form for magnetic concentration. Furthermore, there are in the western, as in the eastern area, two main horizons, one above and one below the "intermediate slate." Through the central part of the range each of these magnetite zones is over 100 feet thick.

As an illustration of the masses which have been drilled without recognition of magnetite, Figure 5 is presented. It is sketched from a reëxamination of cores from drilling, in which a fair body of hematite was discovered—perhaps two or three million tons. Two magnetite bodies are outlined, one about two million and the other ten million tons. These are an average of 55 feet thick, under a drift cover of 65 feet,—less favorably situated than the deposits east of Mesaba, but still worthy of note. The samples of these cores were ground to 100 mesh and concentrated magnetically, 2.83 parts of ore giving 1 part concentrates with an iron content of over 64 per cent.

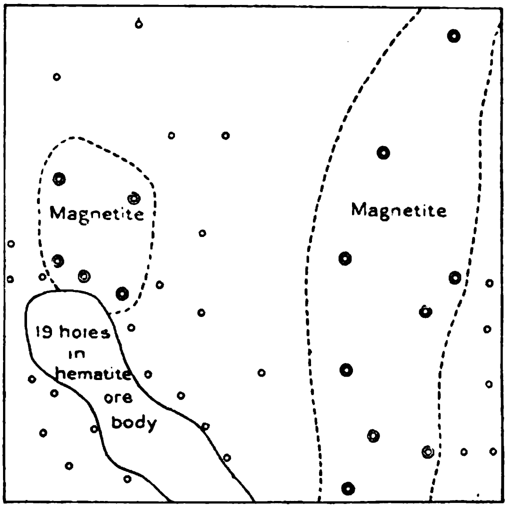

FIGURE 5. SKETCH MAP OF A QUARTER SECTION ABOUT 20 MILES WEST OF MESABA, IN WHICH DRILLING HAS DEVELOPED A BODY OF HEMATITE. THE CORES SHOW TWO BODIES OF MAGNETITE WHICH HAVE BEEN IGNORED, BUT WHICH ARE ABOUT 5 TIMES AS LARGE AS THE HEMATITE BODY.

This discovery that magnetite is a prominent constituent in the fresh taconite of the west Mesabi was unexpected, because of previous reports of the dominance of hematite west of Mesaba.[3] It was also supposed that magnetite is relatively stable under leaching and would not ordinarily alter to a soft hematite. It is very evident, however, that ferric oxide has formed east of Mesaba, by alteration of magnetite. The occurrences of abundant magnetite in the west part of the range in the fresh unweathered iron formation suggest that the protore there also contained more magnetite than hematite.

Magnetic mapping.—The persistence of magnetite across the range and its localization in certain beds of the iron formation might indicate the probability of a successful magnetic search for these horizons. Leith, however, recorded observations along the range indicating much more magnetic effect in the east Mesabi than on the main range and concluded that there is much more magnetite east than west; he also noted that no special horizons were detected by the needle unless it was the zone just above the Pokegama. He found high readings in places near the contact of hematite and fresh taconite.

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[3] Magnetite has recently been noted by J. F. Wolff, Recent geologic developments on the Mesabi iron range: Lake Superior Min. Inst., Proc., vol. 21, pp. 229-57, 1917.

Detailed dip needle and dial compass readings have been taken on lines one quarter of a mile apart, all along the east end of the range, and while the deflections show the boundaries of the iron formation as a whole, it has not been found possible to relate them very definitely to the several horizons. No line of readings crossed the iron formation without finding some high dip needle deflections, and the dial compass was affected somewhat erratically, mostly in the belt of the better magnetite deposits, but it has not been possible to make much use of the data in the detailed mapping or in the search for the richest magnetite. (See the description of the Iron Lake area, pages 52 and 53).

In explanation of the rather weak attraction which is shown by the iron formation of the main part of the range for the magnetic needles used in exploratory work, the following points are mentioned:

1. It has been observed that tabular bodies of magnetite with a low dip to the south, such as is shown by the Biwabik iron formation, may cause very little disturbance of the earth's magnetic field, and hence have little effect on the magnetic needles.[4]

2. The oxidation of the magnetite to ferric oxides to a depth of several hundred feet in many places makes the attraction at the surface weaker.

3. The burial of the iron formation beneath a great thickness of glacial drift has the same effect.

Method of estimating reserves.—With a little more drilling it seems likely that the continuity of the zones of iron concentration through the range may be very definitely established. If it is agreed that the primary magnetite concentrations occur as strata, drill holes spaced several hundred yards apart will give a good check on the location of ore and the amount of drift cover. The estimation of reserves becomes a problem of stratigraphy rather than one of drilling. Detailed drilling will be entirely unnecessary unless it is found to be the best method for the study of the thickness of drift, and two or three variable features which interrupt the formation locally, viz., dikes, faults, and secondary alteration to hematite. With due allowance for these factors, the volume of ore can be calculated with very little drilling.

The quality of the ore also may be estimated in the case of such primary beds with much less drilling than in the case of enriched ores. While there are variations in the quality of beds, the changes are much less abrupt than in the case of enriched ores, and a few holes should give a fair indication of the average ore.

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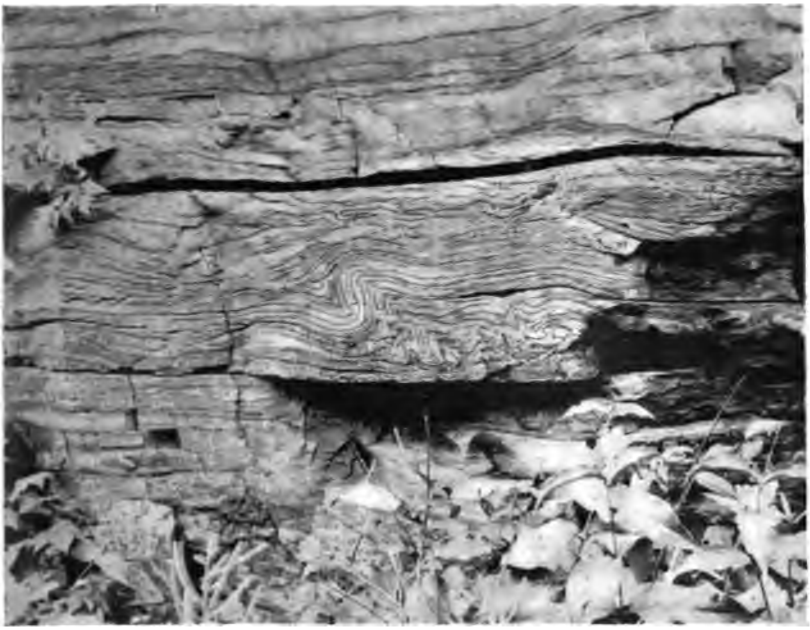
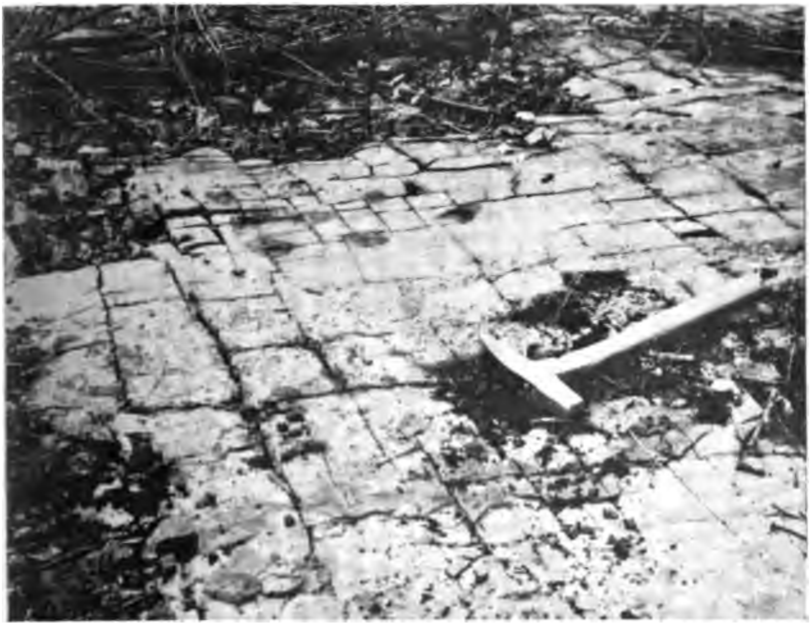
[4] Broderick, T. M., Some features of magnetic surveys of the magnetite deposits of the Duluth gabbro: Econ. Geology, vol. 13, no. 1, pp. 35-49, 1918.



A. DRAG FOLDS IN THE UPPER SLATY BEDS, ALTERNATING WITH MORE COMPETENT LAYERS



B. THE CLOSELY SPACED JOINTS OF THE CONGLOMERATE PHASE OF MAGNETITE DEPOSITS

CHAPTER VII

THE MAGNETITE DEPOSITS—ECONOMIC CONSIDERATIONS

Commercial situation.—It is, of course, a commercial matter to decide whether or not any particular deposit of magnetite is to be classed as ore. Up to this time reports on the Mesabi magnetite have been unfavorable; but the economic features of these deposits indicate that as the reserves of richer hematite ores are depleted they will be worthy of more and more consideration.

The commercial situation naturally varies from day to day. The world war started an increase in the demand for iron, and the statistics issued by the United States Geological Survey show that the production in the Lake Superior district increased greatly in 1915 and 1916.

Iron Ore Produced in Lake Superior District, in Gross Tons

1914	33,540,403
1915	46,944,254
1916	63,735,088

Prices have advanced as the demand continued, and in spite of labor and transportation difficulties new reserves have been discovered and new mines opened. Some old abandoned mines have been reopened, and it has been said that if an iron mine can not be made to pay under such favorable circumstances there seems to be little hope for its immediate future.[1] It seems likely that a well equipped plant might have made a profit under these conditions, if it had been already established on the east Mesabi, but the time was not as favorable for building new plants as for stimulating production from those already built. Two small quarries and the experimental mill at Duluth have been operating recently.

Per cent of iron and volume of material.—The grade and amount of ore must be considered together. Specimens a few inches in diameter may show over 70 per cent iron, but no large volume of such ore is to be expected. Van Hise and Leith[2] dismiss the magnetites with the statement that they are a few inches to a few feet thick in layers with other rocks less rich in magnetite. It is true that beds with 30 per cent or more of iron in a form for magnetic concentration are relatively thin, but the beds with 20 per cent of iron (including some smaller beds with over 30 per cent) make up an immense tonnage. The tonnage and quality of material necessary to constitute workable ore must be determined by mining and milling costs and prices of ore.

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[1] Burchard, E. F., Our mineral supplies, iron: U. S. Geol. Survey Bull. 666, V, p. 3.

[2] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, p. 185.

This report gives simply an indication of the general situation as to grades and quantities.

The upper cherty beds, Aub_4, contain near the top two layers of ore with about 30 per cent magnetic iron, and even more in some places. The lower of these is in places 20 to 30 feet thick and the upper about 10 feet thick. They are separated by a few feet of leaner cherty or jaspery material with a conspicuous algal structure, so that they are easily recognized. If this leaner bed is quarried with the rest, to get a working face 40 to 50 feet high, the grade might be reduced to a little below 30 per cent. The lean bed is easily distinguished, however, and could be cobbed out. The volume of such a bed several miles long and 50 feet thick must be very great, but since it dips at an angle of about 5° there is a relatively narrow belt in which the ore can be worked, with a high quarry face, without stripping off the overlying formation.

The beds mapped as Aub_4 and Aub_5, taken all together with rich and lean beds, and rich and lean areas, may contain as much as 20 per cent of iron available for magnetic concentration. Lean beds, especially near the top, will be partly balanced by the richer beds near the algal chert. Since the drilling shows some areas much richer than others along the belt, it must be remembered that drilling may be needed to select a favorable area. The outcrops shown on the map extend along a belt about 20 miles long and the average width is about 2,000 feet. With a dip of 5° it may be assumed that the northern edge is too thin to be considered for a distance of 400 to 500 feet from the border. South of that, the magnetite beds cover the area mapped to a depth of from 50 to 200 feet, with only a small amount of drift cover at most places. A rough calculation indicates that the east Mesabi range from Birch Lake to Mesaba contains about 1,500,000,000 tons of this magnetite formation within 100 feet of the present rock surface, without any bed rock cover. If such a reserve is to be considered as "available at present," it will more than double the present reserves of the range. The reserves of similar grade farther west are less accessible since they are covered more deeply with drift, but they are very large.

Van Hise and Leith[3] estimated in 1911 that the total present available reserves on the Mesabi were nearly 1,500,000,000 besides the "wash ores." If the lean bodies of "wash ore" of the west Mesabi are to be included, these magnetic ores of the east Mesabi may well be added also. They have certain advantages over other lean ores. For example, Van Hise and Leith[4] include in the reserves available for the distant future, ores that have 35 to 40 per cent iron, regardless of whether or not they are concentrating ores, but add that very little of this ore will be used for a long time, except by mixing with high-grade ores. The advantage of the magnetites lies in the fact that they can be concentrated to a very high grade. This gives a supply of high-grade concentrate which will make it possible to continue mixing in the low-grade ores, long after the naturally high-grade ore is exhausted. Much of the magnetite bed here considered now contains about 35 to 40 per cent total iron, but only part of this iron occurs in the mineral magnetite.

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[3] *Op. cit.*, p. 489.

[4] *Op. cit.*, p. 491.

Topographic situation.—Most of the outcrops of magnetite are on the south slope of the Giants Range and extend with minor undulations down the slope, descending about 100 feet in half a mile. Some of the exposures on the lower southern side are near the level of the swamps or valleys in the slate and not favorably situated for mining, but a large part of the formation stands at high levels and can be mined in open cuts with surface drainage.

Structures.—The beds dip gently and it will not be very difficult to follow the valuable beds down the dip. The bedding planes, though very irregular, furnish surfaces of easy parting.

The joint system in the conglomerate beds is especially favorable to shattering the rock with heavy blasts "against resistance" of previously broken material. The joints are nearly vertical and run prominently about north and south in most places, spaced 1 to 6 inches apart. They are crossed by another set about at right angles. Other sets of joints have been locally noted. Plate XI B shows the prominence of the joints where weathered, but traces of the same structure make the rock break well even at considerable depth.

Magnetism.—The fact that the ores are of magnetic oxides has led to experiments with magnetic milling methods which are so promising that ores of much lower grade than heretofore become of interest. Throughout the east Mesabi the beds designated as magnetite deposits have their iron largely in a form that can be magnetically concentrated. Nevertheless the ore of some of the deposits shows under the hammer a red powder and contains some hematite.

The chemical tests of the several divisions of the iron formation have not been carried far enough to determine why some beds consist largely of iron silicate—fayalite—while others with similar amounts of iron consist of magnetite and quartz. The fayalite is most commonly developed in a quartz-amphibole matrix, but some of the samples have magnetite also, and may be as rich as the rest of the deposit. The matter of combination may be determined by the state of oxidation or by the presence of other elements. Whatever it is, the results are clear;

some beds have considerable iron in magnetic form, and these are the beds distinguished in mapping.

Size of grain.—The grain varies in different beds as well as in different areas, with more or less relation to the distance from the gabbro. The coarser grain is favorable, requiring less fine grinding for the magnetic separation of a rich concentrate. The finer grains remain attached to quartz and silicates which then get into the concentrate and reduce its grade.

The coarse-grained beds, favorable to concentration without the expense of grinding finer than 100 mesh, are the conglomerate beds, Aub_4, and all those that have magnetite east of Dunka River.

The impurities that may be retained in the concentrates, if not ground fine, consist not only of silica, but of phosphorus, which is even more deleterious. The concentrates normally bring a premium because of their low phosphorus. Apparently some parts of the deposits can be made to yield, without special treatment, concentrates so low in phosphorus that the premium is high. Sulphur is normally removed without extra care.

Hardness.—The taconite is one of the toughest, hardest rocks that is quarried. It will always be hard to drill, but the jointing is a great aid in breaking up the rock after blasting.

Milling.—The Mesabi Syndicate have had the benefit of the work of men widely experienced in magnetic concentration, and have built a mill at Duluth in which they have conducted tests of their ore as well as several new devices for milling, and various materials for sintering. The mill has been operating to capacity, producing low-phosphorus concentrates.

Grade of product.—The fineness of grinding and other variable processes in milling permit the operators to determine in advance about what quality of concentrate will be produced. By manipulation of the process, then, the mill can produce any grade of concentrate for which there may be a demand, even those which draw a premium for unusually low phosphorus, and high iron, contents.

In the fall of 1918, a trial cargo of low-phosphorus sinter made from east Mesabi ore was shipped from Duluth to the Midvale Steel and Ordnance Company's blast furnace at Coatesville, Pa. The cargo analysis shows an iron content of 63 per cent, with .008 per cent of phosphorus. It is expected that the concentrates made from these ores to supply the normal demand will run over 60 per cent iron and from .020 to .025 per cent phosphorus.

Transportation.—The distance from market is about equal to that of other Mesabi ores. The Duluth and Iron Range Railroad now has a temporary line along most of the magnetite belt.

Cost of exploration.—It has already been suggested that when enough drilling has been done to satisfy the explorers that the ore beds are continuous, a very few drill holes will give all the data needed as to the quality. It should be much cheaper to explore a property of this regular bedded type, than the irregularly leached deposits of soft ore of the Mesabi.

Scale of operations.—There is plenty of magnetite so that mining operations can be undertaken on as large a scale as at any mine in the world.

Suggestions for conservation.—1. Sampling. Since 1891 when the rush came to the rich ores of the Mesabi range, it has become a fairly established custom to sample drill cores for analysis wherever there was an appearance of enrichment, even if the ore seemed to be lean. On the other hand, hard unaltered looking taconite was of no interest and any lump of core might be thrown in a box as a fair sample for the 5 or 10 feet of core from which it came. In the magnetite bodies all the core looks fresh and unaltered. Nevertheless it is important to have a fair sample. Many of the old cores which have been examined in this work indicate large bodies of magnetic material, but the accuracy of the samples is very uncertain.

2. Magnetic tests. Before a mining property is wholly abandoned for lack of ore, the cores with magnetite should be tested by magnetic concentration to see if any very large body of 20 to 30 per cent magnetite is in favorable position for development.

3. Location of dumps. It has often happened on the Mesabi range that the dump piles from stripping operations and the waste of mining were placed where they had to be moved later, to get some good ore that was unknown at the time. We suggest therefore, that even now before the magnetites are worked, dumps should not cover the better magnetite bodies. It is uncertain how long it may be before the magnetite will be wanted, but when the time comes, the ore should not be inaccessible because of our carelessness in locating dumps. (See Figure 5, illustrating a neglected magnetite body which might be carelessly buried under so much waste that it would not pay to remove it, to get the magnetite.)

CHAPTER VIII

THE ORIGIN OF THE MAGNETITE DEPOSITS

Introduction.—The bedded and banded character of the iron formation taken in conjunction with its mineral composition indicates clearly the sedimentary origin of the material.

Agent of transportation.—Cherts and the several primary sediments of iron, on the Mesabi, are materials known to be precipitated from water solution, and it is generally agreed that in those parts of the formation where clastic grains are lacking, it may be assumed that the iron-bearing sediments were deposited from water solution. No mechanical sediment is known which closely resembles them. The solution of silica may have been facilitated by the presence of alkalies; that of iron would be more likely in the presence of acids. If carbonate minerals were more abundant (as in some other ranges) an alkaline bi-carbonate solution might be suggested as the most probable combined solvent. This kind of solution is known to have had an igneous origin in some places. Incidentally some alkali may have been derived from the granite near by.

Source of the iron.—The source of the iron in the water solutions is naturally a matter of great interest. This question is discussed at length by Van Hise and Leith.[1] They conclude that for the iron of unique, thick, extensive iron formations like this, it is necessary to appeal to contemporaneous basic igneous rocks. Some of the iron may have been derived from the action of water on the rock, either hot or cold, but large parts of it may have been carried in solution by direct magmatic emanations. There is less contemporaneous igneous rock near the Mesabi than in most iron districts, but there was a large amount of igneous activity from the Cuyuna range in Minnesota, to the Marquette district in Michigan, and probably elsewhere.

Deposition.—1. Precipitation.—From any assumed solution, it is easy to suggest reactions that will precipitate silica and iron.[2] The direct evidences of the actual form of the precipitate and the nature of the precipitating agent are very slight. There are the supposed algal forms in the cherts and jaspers indicating organic action. There are also the graphitic cherts and slates indicating organic material. Steiger[3] reports organic matter in some greenalite rock. Since it seems that organisms could live at that time and organisms are known to precipitate iron at the present time, it may be assumed that they played a part also in the deposition of the iron of this formation. This is not certain, because the deposits seem to have been more or less modified since their first deposition, and their original form is in doubt. Leith has shown that material of similar composition and character can be produced by inorganic action in the laboratory, so that the action of organisms is not essential to precipitation. Current studies however seem to indicate that if a reaction may occur both organically and chemically, it occurs more rapidly and completely by the action of organisms. It is therefore believed that organisms precipitated not only cherts, but at times, highly ferruginous cherts. Harder and Johnston refer to the possible precipitation of ferric oxide and silica, as the primary deposits of the iron formations, associated with more or less organic matter.[4] The iron of the Biwabik formation was probably in a combination of a ferrous silicate and carbonate, and a ferric oxide, in proportions varying according to varying conditions.

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[1] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, pp. 506-18.

[2] Van Hise, C. R., and Leith, C. K., *op. cit.*, pp. 519-27.

[3] Steiger, George, See analysis in U. S. Geol. Survey Mon. 52, p. 167.

2. Conditions of deposition. The extent of the magnetite deposits and the associated sediments indicates deposition on a broad sea bottom. The beds lie above a sand and below a clay, as a part of a series of sediments, probably formed in shallow water. Van Hise and Leith[5] consider the water probably shallow, because of the predominance of silicates over carbonates, the structural differences from the Cuyuna iron formation, and the lack of outcrops farther north. An additional evidence appears in the flat form of pebbles in the central conglomerate.

3. Texture of the deposit. The cherts with algal structure appear to be primary in their form and texture. Much of the remainder of the formation is filled with granules, pebbles, concretions, and nodules, indicating more or less reworking since precipitation. Throughout most of the iron formation the granules uniformly show certain mineral and structural peculiarities which have led to the suggestion that they are not ordinary fragmental sedimentary grains. (See Plate IX D.) Leith has argued that the granules of greenalite are forms that may develop in colloidal precipitates by surface tension; or, as he suggested in his earlier paper, by the replacement and coating of organic remains, in some such way as the granules of the Clinton iron formation are supposed to have formed. No doubt there are granules that are best explained as forms resulting from surface tension on precipitates, but there are also many pebbles which could not have formed from any process other than mechanical wear. Associated with fragmental pebbles, granules of similar fragmental origin are certain to be numerous. The writers believe, therefore, that much of the texture

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[4] Harder, E. C., and Johnston, A. W., Geology and iron ores of the Cuyuna district, Minnesota: U. S. Geol. Survey Bull. 660-A, p. 16, 1917.

[5] Van Hise, C. R., and Leith, C. K., *op. cit.*, pp. 214, 604, and 613.

has been modified since precipitation. Over half of the main magnetite deposit of the east Mesabi has the characteristic pebbly texture.

4. The alternation of deposition. The alternation of sediments of several sorts in the iron formation as a whole indicates a probable alternation in the source of supply. The larger alternation of slate and chert shows that deposition occurred under different conditions. On the other hand, the smaller, more often repeated alternation of magnetite with chert having a granule or pebble structure is not taken to mean any essential difference in the source of supply or agents of transportation, but rather an alternation of conditions acting on the material already deposited.

Primary modification of the deposit.—As has been suggested, the repeated alternation of material in the beds now found is believed to be a significant fact in connection with the history of the iron formation. There are hundreds of alternations of fine magnetite and coarser fragmental layers. Rhythmic sedimentation is in some cases due to a rhythmic supply of differing materials. In a broad way, the supply may be ferruginous at one time, slaty at another, and cherty at another. If the material had been derived from volcanic sources, as has been suggested, it seems improbable that these supplies would alternate as many times as the sediments indicate. It is unlikely that there were so many successive flows. Volcanic rhythms should produce alternations on a large scale. Furthermore, climatic rhythms are also larger features. The detailed alternation of beds from a tenth of an inch to 6 inches thick is more likely attributable to seasonal or other occasional changes in conditions. These changes would affect a chemically depositing sediment only if in shallow water, and emphasize the conclusion reached above as to the conditions of deposition.

The conglomerate and granular beds of the lower parts of the magnetite zones are very suggestive as to the conditions that must have prevailed. Most of the pebbles are flat, and vary widely in the degree of rounding. They include no fragments of the neighboring granite and schist, but many closely resembling the underlying beds of iron formation. Their size and angularity indicate no distant source. The irregularity suggests washed lumps of partly hardened mud, or precipitate. The most probable source of the pebbles is a part of the iron formation itself. However, no signs of erosional unconformities have been found in the iron formation. Such a conglomerate is to be classed as *intraformational,*—one formed of material recently deposited and without any extensive transportation. Such conglomerates are reported from several limestone formations with characteristics that are so similar as to warrant giving this siliceous bed the same name.[6] The conglomerate part of the formation, as well as some of the granules, may therefore be attributed to a recent precipitate more or less broken up by wave action. The freshly broken fragments would be large and angular pebbles, those washed about for a longer time would be more rounded, and the smaller grains would become rounded granules.

Most of the pebbles are magnetite. This might mean that an original ferruginous layer resisted the breaking action of the waves longer than some of the freshly deposited silica. Other pebbles, however, suggest another explanation. Many pebbles are cherty with a border of magnetite. It seems that at the time the pebbles were rounded (or possibly since then) some process *enriched* them in iron. Since it is believed that the pebbles formed in shallow water, the logical explanation is that standing water acted on the ferruginous chert, enriching it, much as the ores of the Lake Superior region are being enriched at the present day,—by solution of silica, and possibly, but only to a small extent, by deposition of iron in its place.

This assumption of leaching of silica in a sea where silica was accumulating does not appear plausible unless, as was true in this case, some alternation of conditions is indicated. In a shallow sea the contribution of iron and silica from a magmatic or other source may furnish plenty of material for deposition. But at a distance from the source any addition of fresh water, say from a heavy rain on the adjoining land, would crowd back the depositing solutions and replace them by water that would dissolve and oxidize the deposits, until diffusion and convection again brought in the stronger solution.[7] The volume of fresh water which leached the silica may not have been great enough to modify the composition of the depositing solution very much, after it was mixed by diffusion and general circulation. So the next deposit of iron is not necessarily leaner, or more siliceous than the first. Occasional storms might agitate the waters enough to break up the deposits and round the grains, but the special richness of the conglomerate in iron oxide is thought to be due to a primary leaching of the silica. The enrichment is considered primary because it is believed to have occurred before the overlying layer was deposited. While this enrichment is chemically the same, it is not such an enrichment as has occurred on the main Mesabi range in late geologic periods. That enrichment has been accomplished by circulating ground waters, and may be as deep as the waters carry solvent action. The primary enrichment here considered probably occurred at the bottom of shallow standing water and its effects were superficial. Nevertheless if each thin bed is superficially enriched, the formation as a whole shows the effect. From this point of view the magnetite pebbles may be those which were most thoroughly leached. There may be an analogy in the Cretaceous hematite conglomerates of the west Mesabi, but this is doubtful. The best magnetite is so characteristically associated with conglomerate that there is a strong suggestion that the taconite has rich layers only where leached.

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[6] See for example, Foerste, A. G., Intraformational pebbles in the Richmond group: Jour. Geology, vol. 25, p. 289.

[7] Van Hise and Leith note that some greenalite was probably oxidized at the time of deposition. *Op. cit.*, p. 537.

In continuation of this argument, it is well to consider the end products of such processes of leaching and wave action as are here suggested. Eventually the silica might all be leached from a surface layer, and the residual iron compounds, thoroughly oxidized, might be pretty well pulverized. The conditions in deep water may also be such that a little leaching of silica might occur, leaving only a layer of iron oxide along the bottom. When deposition was resumed, this powdery ferric oxide, however formed, would lie on the irregular bottom as a layer of relatively pure ore. This is exactly the condition of the magnetite beds now alternating with conglomerate.

The suggestion here given as to the origin of the pure magnetite in no way conflicts with the possibility, suggested by Van Hise and Leith,[8] that some oxides may have been precipitated directly in very pure form. Precipitated oxides, however, would be expected to alternate with precipitated chert rather than with a conglomerate.

After any accumulation of oxides, the next precipitate would tend to cement any such layers into fairly firm masses, and the next storm would break them up into pebbles of iron oxide. This is the effect suggested by such outcrops as are shown in Plate IV A, where a bed of magnetite stops abruptly and there are near it some fragments that look as if they were just broken off. Thus both the enrichment of chert pebbles and the breaking up of greatly enriched iron oxide beds furnish ore pebbles to the conglomerate.

The development of nodules in the magnetite deposits is probably not a phase of primary deposition, but is believed to be an effect that developed soon after deposition. In the main conglomerate beds no clear nodules have been noted, but in the thin beds above the algal cherts, the structures can hardly be given any other interpretation. (See Plate VI B.)

Both silica and iron are known to be subject to concretionary rearrangement, and on the west Mesabi some common chert nodules may be seen. There are a few small concretions containing both iron oxide and quartz in concentric bands. It is not generally supposed, however, that most of the small granules involved any concretionary action after their deposition. They have been considered in the preceding paragraphs as fragmental and precipitated granules. The peculiarity of the nodules here illustrated is that, though rounded and elliptical in outline, the internal texture is granular like the matrix and finer parts of the conglomerate. It is evidently a fragmental accumulation which has been incorporated or included in a nodular cement. The nodules are mostly elongated and show gradations into continuous beds of similar material, as shown in the figure (Plate VI B). Both the rounded forms and the irregular layers contain septaria cracks (Plate VIII). Between the nodules are thin beds of magnetite, and the nodules themselves contain considerable magnetite, so that the formation contains about 20 per cent of iron.

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[8] *Op. cit.*, p. 527.

The conspicuous irregularity in the bedding is probably more closely related to these several primary modifications than it is to the original precipitation. Solution surfaces resulting from leaching normally show rounded forms; concretions are irregularly rounded, and the compression of loose sediments against the rounded lumps would no doubt produce some such wavy bedding planes. Considerable irregularity may be due to the shrinkage of voluminous colloidal precipitates during consolidation and recrystallization. The septaria cracks show that some such shrinkage occurred.

Metamorphism.—It can hardly be assumed that the primary deposition and reworking of the iron resulted in the formation of magnetite. The precipitation of magnetite in water at ordinary temperature is not a reaction commonly observed in nature. There is reason to believe that the precipitate was a chert with ferrous silicate and ferrous carbonate and more or less limonite. The oxidation and formation of intraformational conglomerate probably produced limonite. The change from these minerals to magnetite is a kind of metamorphism that may occur in several ways. Probably the ferrous iron of the silicate and carbonate and the more oxidized limonitic beds reacted directly to form magnetite. If the oxidation was very complete, a reducing agent is available in the organic matter, known to have been present in certain beds. These and other reactions have been sufficient, during the long ages of recrystallization under heat and pressure, to make most of the iron oxide of the Mesabi formations magnetite.[9]

The occurrence of magnetite and hematite as adjacent pebbles in a conglomerate, or as an intergrowth, has already been mentioned, but the alteration just outlined offers no explanation of the different state of oxidation of such associated minerals. The ease of alterati ferric oxides to magnetite may be related to certain conditions i primary ore. There might be differences in hydration, or difi admixtures of hydrous minerals. There might be differences in p ity; different amounts of the organic reducing agent; or other liarities of mineral association. Any of these conditions may affec later metamorphism to hematite or magnetite.

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[9] This is not recognized by Van Hise and Leith. It is not necessary to appeal to the reduction or oxidation by water as suggested by them, *op. cit.*, pp. 172 and 527.

The development of several silicates and the coarse grain of n of the taconite may also be attributed to general metamorphism, have had no very great influence on the value of the deposits.

Dynamic metamorphism is indicated by the folded layers and sion cracks. Scattered veinlets of quartz and magnetite prob developed under conditions of great heat and pressure.

The contact metamorphism of the iron formation as a whole been discussed above. It has recrystallized the magnetite near gabbro, increasing the size of grain and ease of magnetic separat It apparently added no appreciable amounts of either iron or titani

Lack of secondary enrichment.—It is likely from the broader r tions of the gabbro that much of the Virginia slate and even the i formation had been eroded before the gabbro was intruded.[10] T may have been enriched portions of iron formation, but if so they h probably been eroded since Keweenawan time. The uniformity of iron content in the fresh taconite from east to west on the Mesabi i cates that before the metamorphism just described there was no enri ment of the rocks now found on the east Mesabi of any such local as that now in progress. Since Keweenawan time enrichment occurred in a few favorable areas.

The three mines of hematite in the east Mesabi are all in the west end of the area, and represent the gradation to the conditions of enr ment on the main range. East of the Spring mine there is practic no effect of weathering. Swamp waters may attack the formation depth of a few inches, but they impoverish it rather than enrich The porosity is said to be less than 1 per cent, as compared to 5 cent farther west.[11] This difference in porosity is thought to be n important than the mineral composition in determining enrichm for the magnetic oxides are found all across the range, and the n netite east of Mesaba has in some cases been altered to the ferric f

Résumé of the history.—Deposition occurred probably in sha water by precipitation, mainly as an organic process, resulting in ferruginous cherts, with more or less siderite, ferric oxide, and gre

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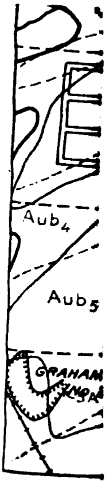
[10] Grout, Frank F., The lopolith: Amer. Jour. Science, vol. 46, pp. 518-20, 1918.

[11] Van Hise and Leith, *op. cit.*, p. 554.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lite. Alternating with periods of precipitation came periods of solution, leaching, oxidation, and wave action, producing intraformational conglomerates, granular rocks much richer in iron, and probably some layers of pure ferric oxide.

The richer deposits of magnetite are so characteristically in the granule and conglomerate zones that we are led to believe that the primary leaching was a determining factor in the development of richer magnetites from lean ferruginous cherts, greenalite rock, etc. Later when covered with other layers, there may have been more or less concretionary rearrangement. Deep burial under slates developed heat and pressure that recrystallized a great deal of the formation. The on minerals reacted at this time with each other and with organic matter, and possibly with other reducing or oxidizing agents producing magnetic oxides of iron. The recrystallization produced shrinkage cracks, and some regional movements developed folds, but seem to have had no important effects on the formation. Contact action by the Duluth gabbro and sills made a great difference in the texture of the deposits at the east end. Erosion has exposed the metamorphosed beds without any important weathering effects on the minerals.

CHAPTER IX

DETAILS OF THE DISTRICTS

The Mesaba area (*Plate XII*).—The two pits of the Gr at Mesaba are the most important recent operations of the ea No detailed examination was attempted, but the walls of show septarian concretions indicating that the enrichmen at the upper magnetite horizon. The algal jasper beds see been somewhat resistant and escaped enrichment, for co amounts appear in the dump.

The Mayas mine, at the lower magnetite zone, was worke hematite of fair but variable quality. It was reopened in 191 manganese that was recently discovered.

One of the best exposures of algal structure appears in northeast of the town along the road.

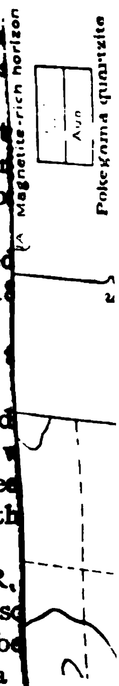
Greenalite, the amorphous green ferrous silicate considere to be the primary precipitate of most of the iron formation, in its best development in the material on the dump of a de the north side of town. Many test pits at the south of t mine have dumps of rock resembling greenalite.

South of the area mapped in detail, in sec. 34, T. 59 N., R a drill hole, reported by Van Hise and Leith[1] to penetrate s and then, passing 576 feet of iron formation, to go a numb into diabase. Diabase outcrops were not seen west of a exposed on the south side of sec. 15, T. 59 N., R. 14 W.

Magnetite rock that appears to have over 20 per cent of magnetic form outcrops in both the upper and lower horizo lower horizons are well exposed in the N.E. ¼ sec. 15, T. 59 N., The higher horizon is exposed near the road, along the south sid 15 and the north half of sec. 22, T. 59 N., R. 14 W., and seems to r the same body of magnetite as the larger exposures farther east.

No detailed work has been done south of the iron formation, approximate contact of the slate and gabbro south of Mesaba i determined by the outcrops along the railroad.

The Spring mine area (*Plate XIII*).—The Spring mine lie valley between hills of Lower-Middle Huronian slates on the and a bluff of slate and slaty taconite on the east. The ore easterly dip, and was enriched down even under the slate out The floor of the ore body is partly the Pokegama and partly olde mations. The concentration and enrichment are discussed in Chapt



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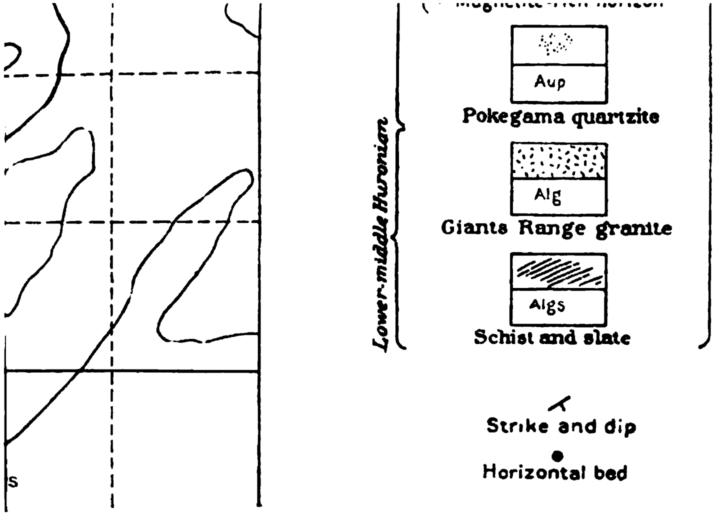
[1] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, p. 177.


S
Aup
Pokegama quartzite
Alg
Giants Range granite
Algs
Schist and slate
Lower-middle Huronian
Strike and dip
Horizontal bed

ne old pit was pumped out in 1917 for further exploration. It is ed to as the "Silverton property," but is locally still called the Spring mine because of a strong spring that issues near by.

The casing of an old drill hole in the western part of sec. 14, T. 59 N., R. 14 W., has a flow of water from artesian pressure. The beds no doubt outcrop in the hill half a mile north. The water is very clear and apparently not ferruginous.

The fold in this area is the largest in the east Mesabi, and may have been a factor in determining the location of the ore of the Spring mine. It is close to the change in bedrock below from granite to slate, but the slate stands at a higher level than the granite under the iron formation. There are intrusives which may be related to the structure. The outcrops may be interpreted as the fold shown on the map and block diagram. The steep dips of the beds in the narrow part of the fold, along the railroad, show that the folding was very sharp. It is possible that some faulting may have occurred also. Small faults may be seen in the slate. The discovery of some outcrops far to the south along the east side of sec. 23 makes the curve considerably sharper than it was previously supposed to be. (See Figure 6.)

It is in the northern part of this area that the Giants Range granite has been supposed to give way to the Embarras granite, a later intrusive on the east. No such intrusive could be found.

The exposures along the railroad south of Spring mine include several that were the bases of interpretation of the geologic history. In the N.E. ¼ of N.E. ¼ sec. 14, T. 59 N., R. 14 W., a few feet east of the railroad, iron formation conglomerate lies on the eroded edges of Huronian slate, with a striking unconformity.

In the S.W. ¼ of S.W. ¼ of the same section, the railroad passes some outcrops of slaty beds that resemble a phase of Virginia slate. The outcrops, however, can be followed directly west in a belt that passes between beds of iron formation, and they are undoubtedly outcrops of the intermediate slate. The slaty outcrops have conspicuous garnet netacrysts, which under the microscope prove to be filled with minute mphibole needles.

The magnetite bodies show some features that differ from those arther east. The upper magnetite horizon is relatively narrow, but he lower, by reason of increased thickness and relatively flat variable lip, shows a broad important area. A preliminary sampling of the rea indicates over 27 per cent of iron in form for magnetic concentration, in an area of almost half a square mile. The thickness of this ower formation is indicated by some drill holes in the next sections ast of Spring mine. They show over 40 feet of this lower bed, containing about 30 per cent of iron. Drilling was done in both sec. 1

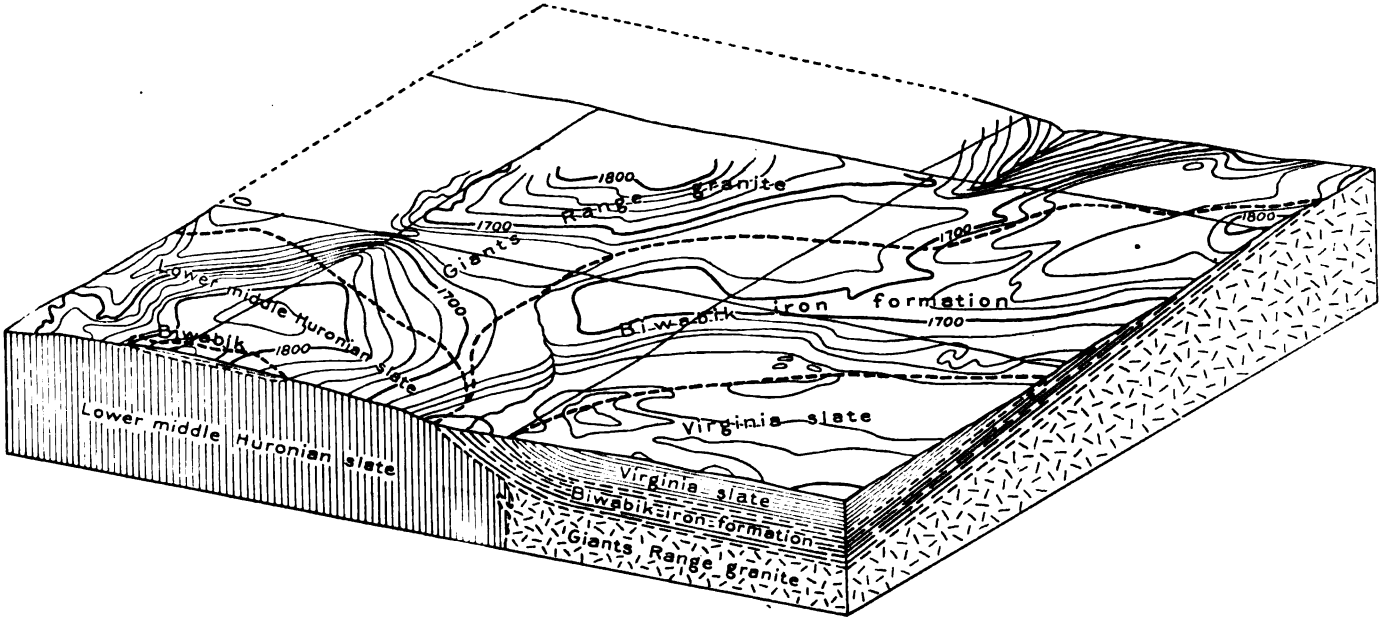


FIGURE 6. BLOCK DIAGRAM OF THE FOLD NEAR SPRING MINE

nd sec. 12, T. 59 N., R. 14 W., and indicates 50 feet or more of the pper body of over 20 per cent magnetite, and from 10 to 61 feet of the lower body in different places. Most of the lower magnetite body ies close to the granite. Plate XIV A, showing the structure, is based n accurate measurements of drilling.

The Ridge area (Plate XV).—The branch of the railroad running along the east Mesabi formerly had a side line turning north just east of Ridge. This passed through a valley transverse to the range. On each side of this low place the exposures of the several divisions of iron formation are very clear. Through most of the four sections mapped, the outcrops are numerous and horizons easily distinguished. Along the south side, however, the limit of the formation is concealed in swampy land.

A few paces east of the center of sec. 32, T. 60 N., R. 13 W., is a small ravine running south through the richest part of the magnetite beds and the intermediate jasper with algal structure. A sample from a bluff 10 feet high showed nearly 40 per cent of iron in form for magnetic concentration.

The northern, lower magnetite belt here seems to become less continuous than it is west of Spring mine, though the several outcrops may be connected under the drift. The lower magnetite beds show more oxidation and leaching than in most outcrops. The lower slaty beds have many soluble silicates and are similarly leached and enriched, developing oölitic or concretionary structures with limonite composition.

A small diabase dike intruding the lower horizons of the Biwabik formation, outcrops in the N.W. ¼ of the N.E. ¼ of sec. 32.

Over 60 drill holes were once put down in sec. 6 and adjoining parts of sec. 5 and sec. 7., T. 59 N., R. 13 W., and the cores have been recently reviewed. They can be correlated closely with the data from outcrops and other drilling. The upper magnetite body is 212 feet thick and the lower about 42 feet thick. (See Figure 4 and Plate XIV.)

The Jericho area.—Two properties in this area have been more or less prospected. Many test pits were put down a little northwest of the center of sec. 28, T. 60 N., R. 13 W., northwest of the old "Syndicate camps." The dumps show a mixture of magnetite and ferric oxides, but enrichment has not apparently yielded a large rich body of ore. The compact specimens on the dump indicate that leaching has not been as thorough as in many places farther west, though evidently silica has been leached. Within a mile southeast of these prospects, in a swampy area, there is a highly ferruginous spring, indicating that iron as well as silica is being removed from the rocks.

The other prospect is the recent opening in magnetite in a bluff south of the railroad siding at Jericho. This bluff is in the gradation zone between good magnetite deposits north and the lean t south. The tests were made on quarry samples and were nc enough to encourage further work. The exposure can be fc southwest nearly a mile along the strike, with fairly uniform acter. North of the railroad are a few outcrops of more pro magnetite.

Through most of this area the outcrops are few, and the d apparently thick. In all of sec. 27, T. 60 N., R. 13 W., onl small outcrops were found. These are of the lean upper beds. T course makes the boundaries as mapped somewhat uncertain.

The Iron Lake area (*Plate XVI*).—The southern part of this is characterized by a series of diabase ridges formed by outcrop sills 10 to 20 feet thick. These can be followed with considerable a racy for a mile or more, and extend with some interruptions m farther. The sills conform to the bedding wherever observed and be used in some cases as a guide to the structure of the other be The dip of the sills is so slight in some places that the topograp slope exceeds the dip, and there are numerous outliers and inliers o cropping in a way which interferes somewhat with the regularity of t belts mapped. The sills are the only conspicuous outcrops in the sout ern area, and it is only in a few places that their roof and floor roc are well exposed. The whole series has been previously interpreted a single sill, half a mile wide, but there are at least four in this area The tops of several of these diabase ridges are a hornfels, clearly derive from slate. Without much question the Virginia slate is continuous from Mesaba to Dunka River.

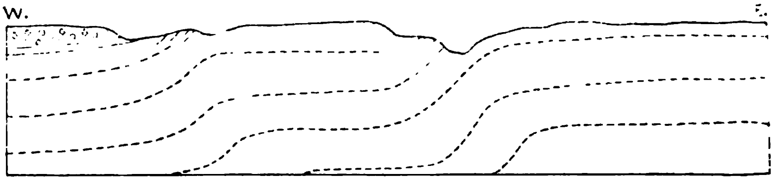
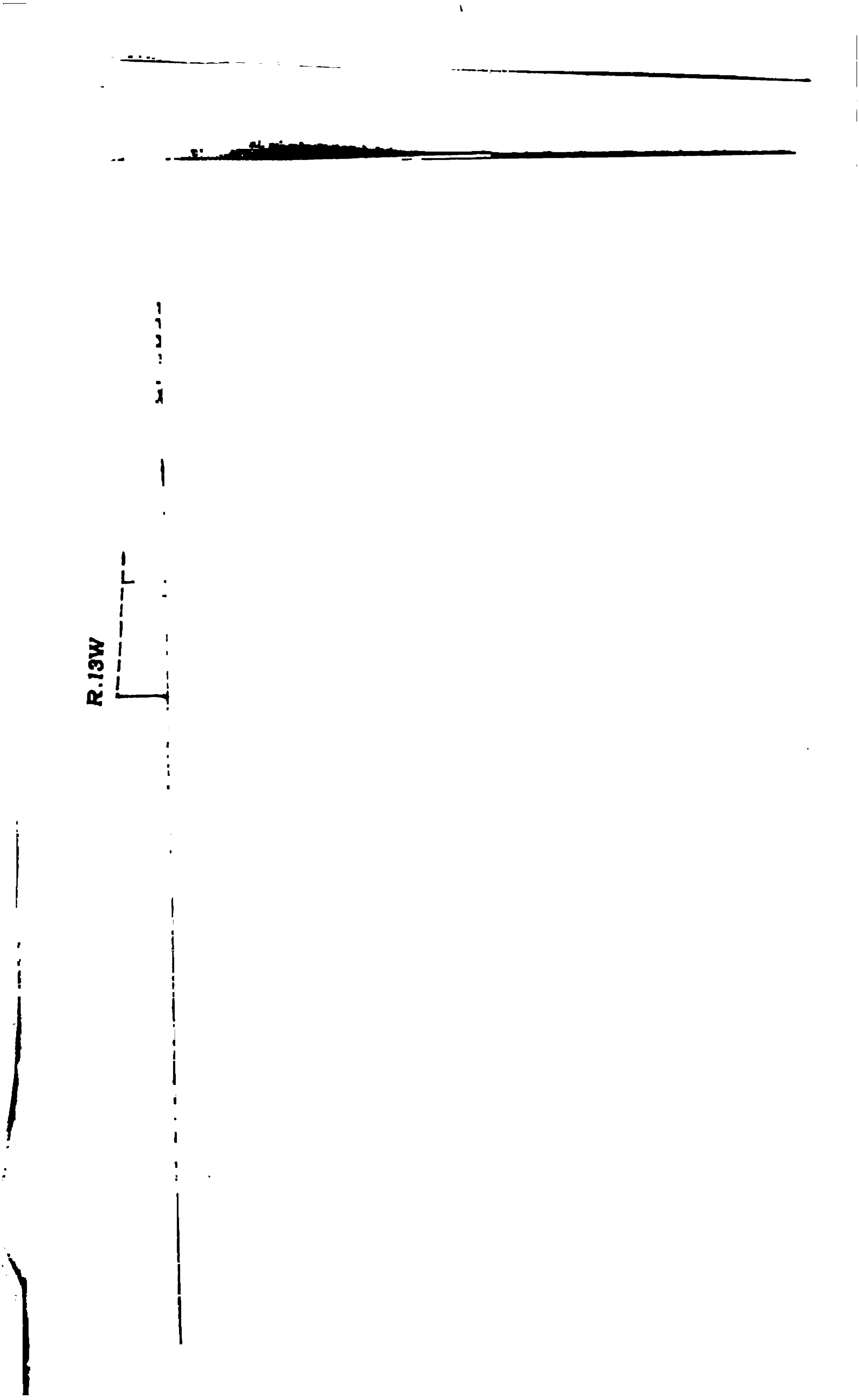


FIGURE 7. SKETCH OF A CROSS SECTION 200 PACES SOUTH OF THE NORTH SIDE OF N.E. ¼ SEC. 25, T. 60 N., R. 13 W., SHOWING OUTCROPS AND (IN BROKEN LINES) THE STRUCTURE SUPPOSED TO EXIST BELOW

Two parts of this area show sharp and exceptional folds a few hundred feet wide. One is in the southwest corner of sec. 26, and one in the N.E. ¼ sec. 25, T. 60 N., R. 13 W. It is assumed from the outcrops in these places that the folds involve the beds above and below to some extent. Figure 7 shows the outcrops in sec. 25, in a cross section interpreting them as two folds. Such a structure, however, may have resulted from displacement along two faults. Figure 8 shows the similar structure in sec. 26.


R.13W

In the Sulphur area there has been considerable exploration of a magnetite body which has been followed into this area in sec. 24, T. 60 N., R. 13 W., with little apparent change in character. In sec. 26 it is probably similar, but outcrops are not so numerous.

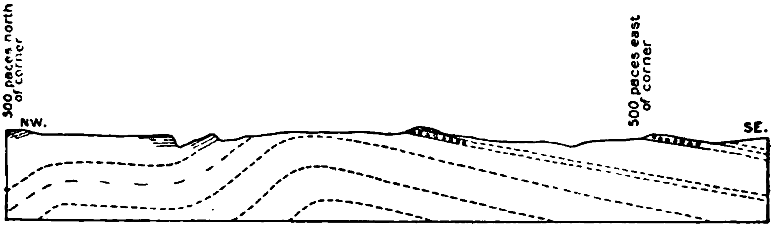


FIGURE 8. SKETCH OF A CROSS SECTION NEAR THE S.W. CORNER SEC. 26, T. 60 N., R. 13 W., SHOWING OUTCROPS AND (IN BROKEN LINES) THE STRUCTURE SUPPOSED TO EXIST BELOW

A strong magnetic pole appears in the magnetic map of this area, located in the east central part of sec. 24. The dip needle gives fairly high readings and the compass needle points in from all sides with surprising regularity. These results were not duplicated anywhere along the range and were thought worthy of a drill exploration. Four holes were put down about 50 feet in rock. Certain layers proved to be rich, but one of the holes struck a concealed mass of diabase, and as a whole the drilling failed to explain the magnetic attraction. The explanation may possibly be found in the topographic situation,—there is a deep valley cutting the beds,—or in the folded or faulted structure, described above.

The Sulphur area (*Plate XVII*).—The outcrops in secs. 18 and 19, T. 60 N., R. 12 W., have long been noted as rich in magnetite. They are located on a hill slope that spreads them out to a greater width than in most of the areas. The irregularity in the belt is due more to the topography than to folding. Practically the whole south slope is a conspicuous outcrop of conglomerate taconite. The amount of iron is about the same as that in the equivalent beds all along the range. Very little hematite is to be found in this area. This is attributed, probably correctly, to the proximity of the gabbro on the southeast.

Along the boundary of the iron formation and the granite, the contact shows more clearly than elsewhere the unconformity between the Upper Huronian and older formations. Not only is there a prominent conglomerate in many places, but there are exposures enough to outline an older erosion surface of considerable relief. Figure 2, page 6, is a section along the general trend of the contact, across the line between secs. 17 and 18, T. 60 N., R. 12 W.

The diabase belt on the map is traced by outcrops well across into sec. 20, but a second sill is revealed by the drilling. The sill between Aub$_5$ and Aub$_6$ has been penetrated in several places by recent drilling. The characteristic texture of Aub$_5$ appears in the core just below the diabase, but there are 20 to 40 feet of this in which the magnetic iron content is less than 20 per cent. It is evident that the upper part of Aub$_5$ is leaner than the bottom, though noticeably of better grade than beds Aub$_6$.

South of the diabase in sec. 20 there are outcrops of gabbro and altered slate. This is one of the best places along the contact of the gabbro and slate to observe the contact effects of the gabbro. The slate develops the hornfels texture and the appearance of a fine-grained gabbro. There are phases that consist of fragments in a matrix, as if part of the slate had been almost a liquid and gathered in some inclusions. Pegmatitic stringers and many contact minerals appear in the mass.

Drilling has been carried over the magnetite body almost all across secs. 17 and 19, T. 60 N., R. 12 W. The exploration has here demonstrated a fair degree of uniformity of the beds, as suggested by their outcrops, but a lean area is found at the east. About 150 holes have been put down, most of them to a depth of 50 feet in rock, but others to greater depths, to determine the general relations. The drilling operations by two or three companies at different periods have been reviewed and correlated. Several holes were placed for the sake of determining the geological horizons and thickness of the formations. No single hole, however, has been carried through the whole formation. The section shown in Plate XIV B is based mostly on outcrops, topography, and surface measurements of the inclination of the beds.

Two quarries have been opened in the magnetite bodies, and many cars of ore have been shipped to Duluth for concentration.

The Birch Lake area (Plate XVIII).—Between the area at Sulphur and Dunka River there are few outcrops. Those that occur along the granite boundary indicate the continuity of the belt of iron formation. On the southeast, there are outcrops of gabbro, turning north, somewhat abruptly, and at the river there is gabbro within a quarter of a mile of the granite. From Dunka River to Birch Lake outcrops are numerous and mapping can be done in considerable detail. Gabbro and granite and intervening sediments are all clearly exposed.

The contact effects of the gabbro extend all through the sediments in this area and obliterate most of the distinctions between beds. It is here that the bands of magnetite and quartz show the strong contrast in color, suggesting some segregation and intensification of banding during contact action. There is evidence of considerable rearrange-

nt, in a thin section of pyroxenite from this area; a black oxide rly replaces parts of the pyroxene.

Certain beds have been recognized, however. Distinguished from leaner beds, the beds with over 30 per cent iron in magnetite can recognized in the central zone of the formation almost to the end he outcrops of iron formation, in sec. 26, T. 61 N., R. 12 W. The glomerate horizon could be distinguished nearly everywhere that formation was seen, in spite of the fact that it was well impreg- ed with pegmatitic stringers from the gabbro. There are also in area beds which can be correlated with the lower cherty algal beds, intermediate slate, and the upper lean beds just below the Virginia e. The sediments, from Dunka River north, are steeply and not regularly tilted, and the strike is variable. Figure 9 is a cross on in sec. 3, T. 60 N., R. 12 W., indicating that the iron forma- has been reduced in thickness to 360 feet. The exposed bodies of netite are very narrow.

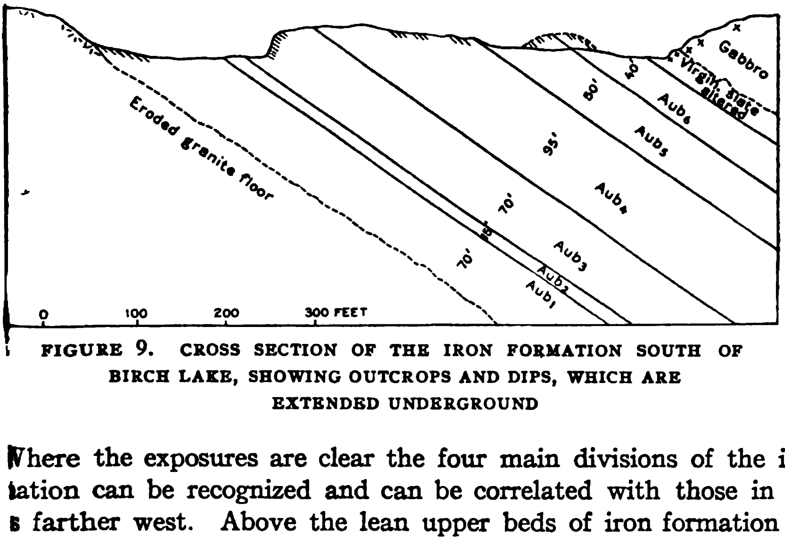


FIGURE 9. CROSS SECTION OF THE IRON FORMATION SOUTH OF BIRCH LAKE, SHOWING OUTCROPS AND DIPS, WHICH ARE EXTENDED UNDERGROUND

Where the exposures are clear the four main divisions of the iron ation can be recognized and can be correlated with those in the s farther west. Above the lean upper beds of iron formation are fine grained rocks with a texture and mineral character identical the hornfels developed from Virginia slate, south of Sulphur Sid- The slate is therefore mapped here much farther north than it heretofore been shown. It has no slaty character, but is easily guished from the coarser gabbro in most places. The gabbro rently cut down a little irregularly into the sediments, for it es through the slate to the iron formation at one place in sec. 3, another in sec. 35. The last large outcrop of hornfels (slate) is er northeast in sec. 35.

Several diabase sills and dikes intrude the sediments near the upper beds of iron formation. The sills are porphyritic, but where the enclosing sediments are altered to hornfels, the sills also become hornfels. They contain phenocrysts which are so characteristic that one may identify them with confidence as the equivalent of the diabase sills in the Iron Lake area; but the sills lose practically all trace of their original diabasic texture.

In the northeast corner of sec. 26 outcrops of gabbro and granite come together, definitely pinching out all sediments. The iron formation was formerly mapped as extending to Birch Lake, probably because outcrops are not abundant, and the iron formation can be found again near the granite north of Birch Lake. This patch north of the lake must be considered an isolated remnant like those farther east along the gabbro contact,[2] for the continuous outcrops of iron formation definitely end south of the lake.

[2] Broderick, T. M., Titaniferous magnetites of Minnesota: Econ. Geology, vol. 12, pp. 663-96, 1917.

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The University of Minnesota

MINNESOTA GEOLOGICAL SURVEY
William H. Emmons, Director

BULLETIN NO. 18

THE
FOUNDRY SANDS OF MINNESOTA

BY

G. N. KNAPP

MINNEAPOLIS
The University of Minnesota
1923

PREFACE

This paper, on the sands of Minnesota, is a report of an investigation begun in 1918, at a time when there was a great demand for information about local molding sands, as a result of the traffic situation that made it difficult or impossible to obtain sands from sources that had previously supplied them. The inquiry, which was in charge of Mr. G. N. Knapp, showed that Minnesota contains an abundance of sands for founding nearly all products, equal to, or better than, the sands that had been imported. Part of the information embodied in the report was placed at the disposal of the metal founders as soon as it became available, either verbally or by means of mimeographed sheets.

The field work showed also that molding materials are more widely spread over the state than was supposed, and a fairly comprehensive reconnaissance was made of a considerable part of Minnesota. Materials gathered from widely separated sources were tested in the laboratory and some were tested by founders in their plants. Minnesota contains an abundance of foundry sands and all materials commonly used for making molds in foundries of iron, steel, brass, and aluminum, except possibly a highly plastic refractory clay.

An economic bulletin such as this is chiefly utilitarian. It should show the nature of materials used, the tests made to ascertain the value of the materials, and the distribution of the materials in the state. These subjects are taken up separately in this bulletin and the geologic and geographic distribution are discussed in some detail. The report does not contain a geologic map. To have included such a map would have resulted in duplication. A search for sands in the hard rock formations will be aided by the use, in conjunction with this bulletin, of the county geologic maps, published by N. H. Winchell and associates in the final report, Volumes I to V, *Geological and Natural History Survey of Minnesota.* The search for materials in the drift will be aided by the maps of surface formations and agricultural conditions, by F. Leverett and F. W. Sardeson, published by this survey, and included in *Bulletins* 12, 13, and 14, already issued. *Bulletin* 11, on the clays and shales of Minnesota, by Professor F. F. Grout and Dr. E. K. Soper,[1] will be found helpful in a search for clay binders, and *Bulletin* 663, of the United States Geological Survey, by Mr. Oliver Bowles, will show the sources of screenings from quarry operations, such as are used to a limited extent.

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[1] Reissued as *Bulletin* 678, United States Geological Survey.

The economic bulletins of this survey are written principally for the use of the general public. We aim to state the results of investigations in terms that are non-technical. If we fail in this respect, and the results of the investigation are obscure, or if they do not contain the information desired, the officers of the survey are available for consultation. The survey charges no fee for such service.

WILLIAM H. EMMONS.

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THE FOUNDRY SANDS OF MINNESOTA

INTRODUCTION

When the Federal government in 1917, as a war measure, assumed control of the railroads of the nation, the founders of Minnesota were notified that the Railroad Administration would not continue to furnish cars for the shipment of sand from remote points, and were advised to find sand nearer home. The writer was detailed to investigate the problem of where foundry sands were to be obtained in Minnesota.

In the course of this work, begun in June, 1918, the southern part of the state from Taylors Falls to the Iowa line and west to Pipestone and Granite Falls was covered in a reconnaissance way by the writer; and Mr. V. T. Allen extended the work to foundries in the northern counties. Sands were found in various parts of the state similar in character and in some respects superior in quality to those which were then in use in the foundries and which had been imported from Missouri, Illinois, Wisconsin, Kentucky, and New York.

Circulars were issued by the Minnesota Survey in 1918 and 1919 on brass sand, quartz sand, foundry loams, and refractory clays of Minnesota, and distributed to the foundries desiring such information.

At the time this work was undertaken there were thirty-five foundries in Minneapolis and St. Paul actively engaged in casting the various metals. Some of them confined their operations exclusively to one line of work such as grey iron founding, steel founding, brass founding, or ornamental bronze founding; others covered a larger field, founding in grey iron, steel, semi-steel, brass, aluminum, and bronze.

Some of the foundries were content to use such sands and loams for molding as could be found in the immediate vicinity of their shops, and could be hauled by team or truck. Others having more exacting contracts calling for high finish to their castings resorted to artificial mixtures of sands and loams, or sands and clays, partly imported and partly obtained locally. Still others had imported all of their sands and clays from remote regions. One foundry doing ornamental bronze work imported a facing sand from France at a cost of $16 per barrel. The sand imported from New York chiefly for brass work, known as "Albany sand," cost f.o.b. Minneapolis about $15 per ton, while sand equally good for the purpose was found in Minnesota, costing 25 cents per ton in the pit, or $3 to $4 per ton at St. Paul.

Time did not permit gathering complete statistics of the amount of sand, loam, and clay used by the foundries of Minnesota, or the cost of the same, but from such statistics as were gathered it is roughly estimated that the total amount used annually exceeded 100,000 tons; and as the price to the foundries ranged from $2 to $15 per ton, it is apparent that the cost is a very considerable sum.

The greatly increased demand within the past few years for a higher grade of casting, both as to the soundness of the casting and as to the finish or exterior surface, more especially in steel, brass, and malleable iron, has led to a great expansion of business in these lines. This demand was augmented by the contracts for war materials, and the rigid inspection and exacting conditions insisted on by the government.

Demand for a higher grade product has brought home to the founder the importance of the sand; the grade of the cast product depends largely on the quality of the sand forming the mold. The percentage of defective castings in some of the foundries visited was so large that the loss incident to scrapping them came near making a loss on the total operation. The defects in the castings, in a large majority of cases at least, were plainly due to the quality of the sand used in the mold or to improper handling of the sand. In only a small percentage of cases were the defective castings due to the metal, itself, or to the methods of handling the metal.

Most of the foundries were without laboratory facilities for testing their molding sands, except by screen analysis and chemical tests; accordingly when confronted by sand trouble that did not yield to empirical methods, they tried another sand usually a new one sought from the locality where some competitor making better castings was obtaining his sand.

In order to appreciate the problems connected with metal founding in Minnesota, most of the plants were visited and samples of the molding sands collected. These were studied in the laboratory. Later various geological formations within the state were studied in the field and samples collected from them. These were submitted to similar laboratory tests, and some of the most promising were supplied to foundries to be tested under actual working conditions.

The laboratory tests to which the samples of sand, loam, and clay collected in the foundry and in the field were subjected consisted in (a) a mechanical analysis, including a determination of the clay content by elutriation; (b) a test of the bonding power or tensile strength by breaking briquets made from the various materials; (c) determination of the porosity by comparing the weight of a given volume of sand with the same volume of non-porous rock; (d) a determination of the permeability by passing a measured volume of air under constant pressure through a core of sand of standard size; (e) a refractory test, which consisted in determining the point of incipient fusion of the materials in an electrical furnace, the temperature of which was controlled; and (f) a mineral analysis.

The following report in which the results of the investigation are recorded is divided as follows: the technology of the sand-consuming industries in brief; the geology of Minnesota with reference to the origin and distribution of sands, as well as some loams and clays; a description of the laboratory methods and the apparatus used in testing; and a tabulation and discussion of the results of the laboratory tests.

ACKNOWLEDGMENT

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Special acknowledgment is due managers and superintendents of various foundries in Minneapolis and St. Paul for courtesies shown; to members of the technical force of these foundries for molding sand specifications, chemical analyses of sands and loams, and other valuable data; and to the skilled molders for the making of special cores and cylinders of molding sand and core sand for permeability tests.

FOUNDING

That certain metals were ductile, and by hammering could be fashioned into implements of war or the chase or into tokens and emblems, was discovered by primitive man in the early dawn of civilization, as evidenced by the relics found in the mounds and burial places of the ancient races.

That the native metals melt at moderate temperatures and that by mixing them in varying proportions, alloys could be made having properties superior for certain purposes to the metals themselves, was no doubt discovered also by early man. This achievement was a prominent one in the "Bronze Age."

The more important discovery that the ores of iron could be smelted and the metallic iron recovered in this manner, marked a still further advance in civilization and was possibly made in prehistoric times, at least such evidence as we have indicates that it was made more than six thousand years ago. The oldest iron implements come from Egypt and date back more than five thousand years. The earliest recorded history has it that Tubal-Cain (B.C. 3875) was known as "master in every kind of bronze and iron work," indicating that the use of the metals had then reached an advanced stage.

Founding, or the art of casting metals, is such a simple matter, now that we are familiar with the procedure, that it seems strange that the process was not discovered and taken advantage of as soon as metallic iron was recovered by smelting the ores. One would suppose that the next step after having discovered the process of smelting would have been to bring the metals into a fluid state and pour it into molds or forms, in this manner casting implements of any form or shape desired.

It appears, however, that the first iron implements were made of wrought iron instead of cast iron; that is, instead of melting the iron and pouring it into molds, it was taken from the furnaces in the form of billets of white-hot metal and hammered into the form desired. So far as now known, wrought iron was used for one thousand years, and possibly two thousand years, before the art of casting the metal was discovered, or at least before cast iron was used industrially.

A discussion of the technique of molding and the methods of handling the melted metal has no place in the present report, except as it may aid those unfamiliar with the procedure better to appreciate the kind of material required for molding sand and for other foundry uses. A very brief outline of one of the simplest methods will suffice, and the reader, interested in further details, may find them in one of the numerous books on foundry practice.

If it is desired to make a sphere or ball of cast iron, or of other metal, the procedure is as follows: First a pattern is made, which is a counterpart of the ball to be cast. The pattern is commonly made of wood but may be made of other materials, such as clay, wax, etc. When made of wood the pattern is made in two parts, with dowel pins or other devices to hold them together and in alignment.

After the pattern is made the second step is to make a mold from this pattern. One half of the pattern is placed on the foundry floor, molding bench, or table, with the flat face downward. Around the pattern is placed a frame of either wood or iron of convenient size. This is simply a box without cover or top into which is packed molding sand until the frame is level full. The molding sand is simply damp sand having enough clay or other binding material in it to hold it together after it is packed or rammed in firmly. The frame, filled with molding sand in which the half pattern is embedded, is next picked up carefully and turned over, bringing the flat face of the pattern uppermost.

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[1] Moldenke, R., Principles of iron founding, p. 2. McGraw-Hill Book Co., New York, 1917.

The other half of the pattern is then placed in position on the half buried in the sand. A second frame is placed upon the first; the surface of the sand in the first is sprinkled with dry sand or dust to make a parting, so that the molding sand to be rammed in will not stick to the sand in the first frame. The second frame is then rammed full of molding sand level with the top. The upper frame, filled with sand, is then lifted off, and the halves of the pattern removed from the sand, leaving an impression, or "mold," in the sand the exact size and shape of the halves of the pattern. The two frames are again placed one upon the other in exact alignment so that the spherical cavity, or mold, in the center of the sand mass will be a sphere. The two frames are then locked together and weights are placed upon the upper surface of the sand.

In ramming in the sand a small hole, called a "riser," is left from the face of the pattern to the surface of the sand in one of the frames. This serves as a passage through which the melted iron or other metal may be poured into the mold.

The frames above described constitute a "flask." A flask is simply a rigid container made of two or more parts and serves to hold the rammed sand in position so that it may be lifted, carried around, or turned over. It also serves to reinforce the sand against the pressure of the metal and against the steam and gases generated in the sand when the hot melted metal is poured in. Flasks vary from simple one-piece boxes to complicated many-piece devices and in weight from a fraction of a pound to many tons.

After the different parts of the flask are in position so that the mold is complete the melted metal is poured into the mold and allowed to stand for a period varying with the size of the casting from a few minutes to an hour or more. As soon as the metal is set, and usually while it is still red hot, the flask is lifted apart and the metal casting is shaken out on the foundry floor where it lies in the loose sand until cooled sufficiently to handle.

As soon as the molding sand has cooled to room temperature, it is used again, the process being repeated as long as the sand has binder enough to stand up in the mold. Clay or new loam is added from time to time to replenish the bonding material which is destroyed by the heat.

Some cast articles are so small or have so many reëntrant angles, that it is not feasible to make two-piece patterns. In such cases a pattern is made of wax, which is a counterpart of the article to be cast. This wax pattern is embedded in the molding sand in a metal flask. The molding sand is then heated to a temperature sufficient to burn up or vaporize the wax which disappears leaving a mold in the interior of the sand mass, which in turn is filled by pouring the metal into the mold. This process is commonly employed in casting ornamental tablets and figures in bronze, aluminum, etc., and is extensively used in modern dentistry in casting gold fillings, and other restorations for teeth. In fact the adaptation of casting in metals, and the diversity of patterns, materials, and processes are almost unlimited.

NATURE OF SANDS AND LOAMS FOR FOUNDRY MOLDING

A great variety of earthy materials is used in the modern foundry under the general names of loam, clay, and sand. The loams used include material ranging from very fine silts to coarse sandy materials with a greater or less amount of gravel, and a clay content ranging from 2 to 10 per cent. The sands used range in mineral content from pure quartz sand to material bordering on loams, in which a variety of materials is present, with more or less clay; and in size of grain they range from material the bulk of which would just pass the 20-mesh screen, to material the bulk of which would pass the 100-mesh screen. Foundry clays range in physical constitution from the purest clay obtainable to ordinary loams, and in refractoriness from the highest testing fire clay to the ordinary glacial clays with a high content of lime and other impurities causing them to fuse readily.

The sands and loams used in the foundry for molding purposes may be divided roughly into classes, according to the function which they perform, as follows: (1) sands used for making the cavities or holes in the metal castings; (2) sands or loams used to make the mold or container which gives the casting its exterior form. The former are called core sands, and the latter are called molding sands or loams.

CORE SAND

For core work a clean sand free from clay is preferred. To this clean sand is added some organic bonding material such as glue, resin, linseed oil, molasses, etc. The heat of the metal will destroy the bond, leaving the core sand incoherent so that it may be readily removed from the cavities of the casting. Greater permeability is obtained in this manner than is possible where loamy materials are used.

The texture and quality of sand used for core work vary greatly and depend on the nature of the founding. If the cores are surrounded by large masses of metal and the temperature of the melt is high, a greater degree of permeability in the cores is required than if the metal mass is small and the temperature low. Where a high degree of permeability is required, a sand of coarse texture in which little or no silty material is present is generally used. If the temperature of the melt is low or the mass of the casting is small, finer sands give satisfactory results for core work.

Quartz sand entirely free from clay is preferred for core work, but it is seldom found in nature in commercial amounts, and sands with one and two per cent of clay are in common use. Glacial sands having a varied mineral content are also used.

MOLDING SAND

As generally defined a molding sand is a siliceous sand having a clay content just sufficient to bind the sand grains together, but not enough to fill the voids between the sand grains; so that when moistened slightly the mass may be molded into any form desired, retaining this form when dry and being sufficiently open or permeable so that air may be blown through it.

The chief requisites of molding sand, then, are permeability and tensile strength or ability to resist rupture. Molding sand must be permeable because when the hot liquid metal is poured into the sand mold considerable volumes of steam and gas are generated in the sand. These must have the opportunity for ready escape, otherwise the mold will be blown to pieces by accumulated gas pressure before the metal has opportunity to set or cool. Molding sand must have sufficient bond so that the walls of the mold will stand up against the pressure of the liquid metal, which in large castings is considerable, and it must withstand the wash of the liquid metal as it is poured into the mold.

Permeability and tensile strength requirements differ, consequently there is no exact standard to which all must conform. In certain classes of founding large volumes of gas are generated in the sand and a high degree of permeability is required, whereas in other classes of work but small amounts are generated and much less permeability is satisfactory. In the same manner the tensile strength or bonding power required of molding sand varies with the character of the founding. Accordingly a certain sand may be entirely satisfactory for one class of molding and unsuited for another.

Other requisites of molding sand are certain textures and refractoriness, but these also are measured by relative rather than absolute standards and depend on the class of founding done. For example, if the temperature of the melt is high, say 3000° F., the molding sand can have but a small content of lime, alkalies, iron oxide, and other fluxing impurities; otherwise the sand in contact with the metal will be fused or melted and will stick to the casting. For such work a refractory molding sand is essential. If, on the other hand, the temperature of the melt is less than 1000° F., as in most brass work, there is little likelihood that the sand will be fused, and refractoriness as a property of such molding sand is for practical purposes negligible.

The texture required of molding sand also varies with the class of founding. Some metals when melted are much more fluid than others and the fluidity of the same metal increases as the temperature is raised above the melting point. If the molding sand is very open and porous and the melt is of a high degree of fluidity, the liquid metal will penetrate the sand or "search the sand," as the molders say. If the sand is exceptionally coarse in texture the face of the mold will be pitted and the surface of the casting made will be rough. For certain types of metal and for certain requirements of finished surface, molding sands of finer texture are required.

Since a molding sand consists of a mixture of sand and clay it may be made artificially by mixing clean sand with the required amount of clay to give the desired bond. In fact, some foundries prefer molding sand made in this manner. But in nature, sands and clays occur ready mixed in every conceivable proportion and most of the molding sands and molding loams are these natural mixtures.

There are no simple tests and no infallible rules or formulae by which the inexperienced may judge whether or not a loam or sand may be suitable for molding purposes but the skilled molder can usually judge the suitability of a given sand or loam for molding purposes by simply kneading it in his hands and by blowing air through it after molding it. The only satisfactory way for the layman to determine the probable value of such material for foundry use is to submit samples to experienced molders or foundrymen, or have the same subjected to laboratory tests.

"DOCTORING" MOLDING SANDS

It is well known that sands and loams as they occur in nature are rarely uniform in character. In any sand bank or pit the material usually varies in character from the surface downward, as well as laterally; so that even if a sample of material is found having the right constitution for molding, there is no assurance that any considerable deposit will be found of exactly the same character. In actual foundry practice variations in the sand or loam are anticipated and the material is brought to the desired consistency by adding the constituents that are lacking. If the loam is too heavy and lacks permeability, clean sand is added; if it it too sandy and lacks bonding power, clay or heavier loam is mixed with it. Coal screenings or ground coal, called "sea coal," is sometimes added. Sawdust, chopped straw, and other similar organic materials are commonly used to give the desired texture and increase the permeability. Organic materials, such as glue, molasses, flour, stale beer, resin, linseed oil, glucose, etc., are frequently employed to increase the bond. This practice of modifying the consistency by adding certain constituents is called "doctoring" the sand.

After the sand has been used in the mold one or more times, the bond is destroyed to a greater or less extent by the heat and the burned products accumulate in the sand as fine silty material, decreasing the permeability and changing the texture. Before being used again, the sand is doctored by adding such materials as will bring it back to the desired consistency. Thus the molding sand, which is continually deteriorating with repeated use, is restored to the proper consistency as to texture, bond, and permeability by repeated doctoring which may consist in adding a single constituent or several constituents. In the ordinary foundry doctoring the sand is a part of the daily or hourly routine and taxes the skill and judgment of the molder to the limit. The grade of casting produced in a foundry, so far as soundness and exterior finish are concerned, depends largely upon doctoring to keep the sand to a uniform consistency.

OUTLINE OF GEOLOGY OF MINNESOTA

The materials used in the foundries include a rather wide range of products of rock weathering, i.e., different types of sands, loams, and clays that have been redistributed and redeposited by wind, glaciers, rivers, lakes, and the sea, and as now found are frequently far from their original sources. In view of this it was believed that the origin of this foundry material might be better understood and its variation in character better appreciated if a description of the material itself was prefaced by a brief account of the general geological relations of the state, the rock formations present, and the sequence of events leading up to the present disposition of the surface materials. In the following geological description the writer has borrowed freely from previous published reports on Minnesota geology.

All of Minnsota except the extreme southeast corner is a broad glaciated plain differing only in minor details from the adjacent regions to the west, north, and east. The minor topographic features of this great plain are the result of glaciation and stream erosion that has taken place in postglacial time. They consist of:

(a) Numerous belts of low knolls or gravelly hills, known as terminal moraines in which are innumerable small undrained basins, kettle holes, or ponds. These moraines represent the material that accumulated at the margin of the glacier in various stages of its advance and retreat and consist of a mixture of all types of material that was picked up from the local rock formations over which it passed. This morainic material, known as "glacial till," while exceedingly heterogeneous in mineral content and physical character, at many places contains material that can be used in foundry work, as the detailed description shows.

(b) Broad, gently sloping plains or prairies of more or less well-assorted gravels and sand, known as outwash, usually fronting the terminal moraines, or otherwise definitely related to them, and representing the material carried out from the ice margin by glacial waters. These gravel plains are usually mantled by loam a few feet in depth, which is serviceable in foundry work, but the sands beneath rarely are.

(c) Broad, comparatively flat tracts in which occur occasional low hills or knolls and many shallow ponds or lakes. These tracts are underlain by glacial till, known as ground moraine. The surface mantle of loam so persistent throughout the state is usually, though not always, present in these areas but is not ordinarily so well suited to foundry purposes as the loams otherwise disposed.

(d) Long, gently sloping plains, usually narrow, that follow the present valleys or the lines of drainage in glacial time. They are underlain by gravels and sands more or less assorted and stratified. Some of these are similar in origin to the outwash plains and frequently are only continuations of such plains, whereas others are postglacial in age and represent the material redistributed by streams since glacial time. They are sometimes called valley trains. The usual mantle of surface loam is common in these areas and often affords good foundry loam.

(e) Narrow plains of gravel and sand more or less well assorted that skirt the border of extinct lakes of glacial age. They seldom carry material of value in foundry work.

The glacial material varies in thickness from 0 to 500 feet. If it were spread uniformly over the area where now found, it would be less than 100 feet thick. It is in reality only a veneer that mantles the topography of pre-glacial time and serves merely to mask the minor details of that ancient surface in some places and to conceal them entirely in others. In a major way Minnesota was a broad low plain in pre-glacial time, on which were well-established lines of drainage with broad shallow valleys and the usual minor topographic features characteristic of stream erosion. The bed rock of the old formations appears at the surface at innumerable places in the glaciated area where the glacial drift was originally thin or absent and where subsequent stream erosion has uncovered it.

At present Minnesota stands somewhat higher than in pre-glacial time. The southern portion of the state, considered broadly, is a low plateau with one elevated area in the southwest corner of the state, known as the Coteau des Prairie, rising to an altitude of 1,900 feet, or about 500 feet above the general level, and a second domed or elevated area in the southeast corner, rising to 1,400 feet above sea level, which is about 400 feet above the general level.

Northern Minnesota possesses a more varied topography. The northwestern part is as flat as a floor, except for a series of low ridges, being the site of the ancient Lake Agassiz. The extreme northeast part of the state is more rugged with several low "ranges" rising to altitudes of 1,800 to 2,000 feet.

The southeast corner of the state, representing about one sixteenth of its total area, is altogether different from the rest of the state in topographic appearance. In a portion of this area, in Houston and Winona counties, glacial drift is absent and probably was never present. It is a part of the so-called "driftless area" of the upper Mississippi Valley. Here natural lakes and ponds so abundant in the rest of the state are entirely absent and the surface everywhere slopes toward the streams that drain it.

Bordering the Mississippi River in this area the tributary streams coming from the west have cut valleys 200 to 500 feet deep, which in places are gorgelike and in other places are flat-bottomed, walled in by cliffs of massive limestones and sandstones of the old Paleozoic formations. Between the valleys the upland areas are commonly rather flat or very gently sloping, plateau-like in aspect, and are remnants of an old plain of stream degradation developed in pre-glacial time when the land stood much lower than now.

The uplands in this area are more or less completely covered by a siltlike loam called loess, to be described later, 0 to 40 feet in depth, which mantles the high points and reaches down the valley slopes even to the streams in places. The old rocks native to the region are largely buried by this loess but in the steeper slopes they protrude and exposures are seen in abundance.

The rocks of Minnesota[2] range in age from the most ancient known as the Archean to the youngest which are now in the process of deposition along the present streams and in the lakes and are known as recent. The accompanying tabulation shows the principal formations present in the state arranged in their proper sequence with the oldest at the bottom. It will be observed that there are two breaks in Minnesota's stratigraphic

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[2] Winchell, N. H., Geology of Minnesota: Final Report Geol. and Nat. Hist. Survey of Minnesota, Vols. 1 to 5, 1882-1900.

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TABLE I. GEOLOGIC COLUMN OF MINNESOTA

Era	System and Series	Formation	Approximate Thickness	Character of Strata	Value for Foundry Use
CENOZOIC	Recent	Recent	0 to 300	Sands, silts, clays, muds	Little or none Valuable
	Pleistocene	Glacial	0 to 600	Loess, gravel, sand, loams, clays	Loams valuable, sands less so
MESOZOIC	Cretaceous	Benton shale Dakota formation	0 to 550	Clays and shales Sands, clays	Clays valuable, sands less so
PALEOZOIC	Devonian		100	Sandstones and limestones	No value
	Ordovician	Maquoketa	100	Shale and limestones	No value
		Galena Decorah Platteville	230	Limestone Shale Limestone	No value
		St. Peter	80-200	Sandstone	Valuable quartz sand
		Shakopee	100	Dolomite	Small value
		Oneota	75-200	Dolomite	Small value
	Cambrian	Jordan	75-200	Sandstone	Most valuable quartz sand in state
		St. Lawrence	100-200	Dolomite and shale	No value
		Franconia	50-100	Sandstone	Little or no value
		Dresbach	300-450	Sandstone, shale, and limestone	Little or no value
PROTEROZOIC	Algonkian	Red Clastic series in southern Minnesota, sandstone in northern Minnesota	2,250 maximum	Sandstones and shales	Kettle River sandstone valuable for quartz sand Other sandstones also
	Keweenawan	Conglomerate and sandstone	500	Conglomerate and sandstone	Little or no value
		Eruptives	Unknown	Igneous rocks	No value
	ALGONKIAN HURONIAN Upper Huronian (Animikie Group)	Intrusives	Unknown	Acid and basic igneous rocks	No value
		Virginia and other slates	3,000	Slates	No value
		Biwabik and Gunflint	800	Taconite, iron ore, chert	No value
		Pokegama	200	Quartzite, Sioux quartzite	Valuable for quartz sand
	Lower Middle Huronian	Giant Range	Unknown	Granite, dolomite porphyries	No value
		Graywacke	5,000	Slate, graywacke, conglomerate	No value
	ARCHEAN Laurentian	Residual clay		Residual clay	Possibly valuable
		Igneous rocks	Unknown	Granites, schists, porphyries	No value
	Keewatin	Soudan	Unknown	Banded cherts and jaspers, iron ore	No value
		Ely and other formations	Unknown	Greenstone, schists, porphyries	No value

record. One occurs between the Ordovician and Devonian, the Silurian rocks being absent; and a second occurs following the Devonian, the Carboniferous, Permian, Jurassic, and Triassic rocks being absent. The Cretaceous is found lying directly on the Devonian and older formations.

Archean period.—The rocks of the Archean system in Minnesota are divided into two groups, i.e., the Keewatin group at the base and the Laurentian group above. The Keewatin epoch was one of vulcanism and the rocks of the Keewatin group consist largely of lava flows that are for the most part basic. The land evidently stood low for water-laid sediments were deposited alternating with the lava flows.

The entire series of beds was subsequently complexly folded and profoundly metamorphosed converting the basalts into green schists now seen in outcrop in much of the northern part of the state.

The Laurentian epoch resembled the Keewatin in that igneous activity was dominant, but the igneous material was intruded instead of being extruded as lava flows.

The rocks of the Archean period in general are of little value for foundry purposes unless it shall be found that some of the more refractory schists may be serviceable for furnace lining.

Algonkian period.—The rocks of the Algonkian period are divided into three groups which from the base upward are known as the Lower-Middle Huronian, the Upper Huronian, and the Keweenawan.

As compared with the Archean the Algonkian period was one of sedimentation, but pronounced igneous activity occurred at intervals during which times igneous material both basic and acid and of several types was intruded in the stratigraphic series.

At the close of the Middle Huronian epoch the region was lifted above sea level and more or less erosion occurred, resulting in an unconformity between the Middle and the Upper Huronian groups.

The water-laid sediments of the Algonkian period consisted of gravels, sands, and muds which as the result of complex alterations by both chemical and dynamic metamorphism were changed to conglomerates, sandstones, quartzites, shales, and slates. Some of these formations, as will appear from the more detailed description, yield foundry sand, particularly the quartzite at New Ulm and the Sioux quartzite (pp. 18 and 19).

The Red Clastic series.—Above the Keweenawan beds there appears a group of beds known as the Red Clastic series, about 2,250 feet in maximum thickness, consisting of shales and sandstones, which are provisionally referred to the Algonkian. Locally this group carries sandstones of exceptionally high quartz content such as the Kettle River and Hinckley sandstone and certain sandstones in vicinity of Duluth which furnish good sand for refractory purposes both for foundry and for steel furnace use.

Cambrian period.—At the close of the Algonkian period all of Minnesota stood above sea level and there was a prolonged period of subaerial erosion and decay of the old crystalline rocks. The region remained in this relation through the greater part of the Cambrian period and not until late Cambrian time did it subside, permitting the sea to encroach from the south and west, resulting in the deposition of sand, sandy muds, and sandy limestones over the greater part of southern Minnesota. The northern part of the state probably remained above sea level throughout Cambrian time and continued to suffer erosion instead of deposition.

The Cambrian group of beds in Minnesota consists of four formations which from the bottom upward are known as the Dresbach, Franconia, St. Lawrence, and Jordan. The Cambrian sea was shallow throughout the period and the long period of subaerial decay preceding the Cambrian submergence had prepared a vast amount of soft and loose material for redistribution by the shallow Cambrian waters. This is evidenced by the incomplete sorting of the material in the Dresbach and Franconia formations, and the rapid alternation of thin beds of fine sand and sandy mud in these formations.

In the last epoch of the Cambrian period, i.e., the Jordan, conditions were somewhat different, either as to supply of material or as to depth of the sea, with the result that a quartz sand of exceptional purity was deposited over a wide area in the southern part of the state.

There was little if any orographic movement during the Cambrian period and there has been but little since, so that the Cambrian beds have hardly been disturbed and very slightly altered in most places. The Cambrian beds lie in nearly horizontal position much as they were deposited and in many localities are so slightly cemented that they may be mined with steam shovel or by hand without the aid of blasting.

The Cambrian formations carry many beds of sand that locally are sufficiently well assorted and of sufficiently clean quartz to be valuable for foundry purposes; but the uppermost member, i.e., the Jordan, so far exceeds the other formations in the quality and abundance of the sand that the other Cambrian formations are hardly worth special consideration.

Ordovician period.—There was apparently no elevation of the region at the end of Cambrian time—on the contrary, probable further subsidence—and deposition continued without interruption into the Ordovician period. The first deposits were calcareous muds now recognized as the Oneota and Shakopee dolomites through which appear numerous thin beds and lenses of quartz sand often remarkably clean and not unlike the Jordan.

After the deposition of these calcareous muds of the Shakopee, there was a slight elevation of the region, shallow water conditions prevailed over a remarkably wide area and a quartz sand, known as the St. Peter, was spread over all of southern Minnesota and adjacent parts of Wisconsin and Iowa, reaching far southward into Illinois, Missouri, and beyond. For uniformity of material and areal extent, this is one of the most remarkable formations in the United States. About the continental border to the northward the slight elevation at the beginning of St. Peter time probably brought the Jordan formation above sea level. The Jordan here was eroded and redistributed, thus contributing in part to the St. Peter deposition; but the original crystalline rocks to the northward, deeply decomposed, were probably the chief source of this great supply of quartz sand.

Following the St. Peter epoch there was a slight subsidence of the region and the recurrence of conditions favorable to the alternate deposition of limestones, muds, and clays which are now recognized as the Platteville limestone, the Decorah shale, the Galena limestone, and the Maquoketa shale. The shale formations in this series afford much clay which is being used extensively in the manufacture of brick, terra cotta, tile, etc., but because of the large content of fluxing impurities these clays are of little interest in foundry work. The Ordovician series of beds is of chief interest to the foundry industry for the supply of quartz sand afforded by the St. Peter formation described in more detail in the following pages.

Devonian period.—With the close of the Ordovician period the region was again elevated and remained above sea level throughout the Silurian period, after which subsidence again occurred sufficient to allow the sea to encroach upon the southern part of the state, causing the deposit of the Devonian limestone 50 to 100 feet thick, together with some shale.

Cretaceous period.—Following the Devonian deposition the region was again elevated and remained above sea level for a very long time, i.e., throughout the Carboniferous, Permian, Jurassic, and Triassic periods.

The elevation was apparently slight and not much erosion was accomplished. The relations, however, were such as to permit the decomposition of the old crystalline rocks to considerable depths; the feldspars were changed to kaolin or clay in which the quartz and other resistant mineral remained embedded, the sedimentary rocks such as sandstones and quartzites disintegrated into sand, and the limestones were leached, leaving a clay residuary. Thus there accumulated a great amount of loose or soft material ready for redistribution when later the region again subsided and the Cretaceous sea encroached upon the land.

This sea encroached upon Minnesota from the south and west re-working the accumulated products of rock, weathering and redistributing them, depositing sands and clays with some limestone upon the upturned edges of the older eroded formations. It is thought the Cretaceous deposition reached as far north and east as the Mesaba Range.

After the Cretaceous period the region was again elevated and stream erosion carried away much of the material that had been deposited but considerable areas in the southwestern part of the state remained, and detached areas or erosion remnants of greater or less extent are found in other parts of the state. These afford valuable supplies of semi-refractory clay and some sand of importance in the foundry industry, as appears in the more detailed description of these deposits which follows.

Pleistocene.[3]—Just before the Pleistocene epoch began the larger features of the topography of Minnesota were much the same as now. The advance of the ice, however, scoured out some valleys, filled in others, and deposited drift over large areas, entirely changing the details of topography and drainage. The retreat of the ice, by melting, formed marginal lakes and swollen, heavily silted streams, with further deposition and modification of topography.

The Pleistocene deposits show a peculiarly complex history, recording not only recurring stages of glaciation separated by long stages of deglaciation but also a complexity of ice movement within a single glacial stage. In the latest stage (known as the Wisconsin stage) there was one movement into Minnesota from the northwest, another from the north, and a third from the northeast; and possibly there was similar complexity in earlier stages. These movements were not synchronous in their advance, culmination, and waning, but each had its time of waxing and waning.

The oldest glacial deposit, known as the pre-Kansan or Nebraskan drift, is almost completely buried beneath later deposits. The attenuated edge of this drift may be exposed outside the Kansan drift in the southeastern counties.

Clayey and silty deposits found in a few places under the Kansan drift may represent accumulation in the Aftonian interglacial stage. They are, however, thin and of small extent.

The Kansan drift is extensively exposed in the southeastern part of Minnesota and in Pipestone and Rock counties in the southwestern part. It is generally of clayey texture, but as a rule carries limestone pebbles. It contains local pockets or lenses of marly pebbleless clay.

Weathering has somewhat modified the character of the upper part of the Kansan drift and wind has coated much of the surface in the southwest corner of the state and some of it in the southeast part with several feet of loess, a pebbleless deposit of fine dust. Recent wash has moved some loess and some drift down sloping hillsides and so mixed them that the precise mode of origin of some particular clay banks may not be easily determined.

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[3] Leverett, F., Clays and shales of Minnesota: U.S. Geol. Survey, Bull. 678, p. 77, 1919.

The Wisconsin gray drift, which was deposited by an ice sheet moving from Manitoba across western and southern Minnesota, is largely of clayey texture, but, like the Kansan drift, contains many pebbles, a large part of which are limestone. In places some lenses and pockets of pebbleless clayey material are included in the stony clay.

The Wisconsin drift that was deposited by glaciers invading eastern and central Minnesota from the north and northeast is in large part stony and sandy and contains very few bodies of silt or clay.

Locally streams of water from the melting ice spread fine sandy clays over what are called outwash plains.

The lake silts laid down in bodies of water in the western part of the Lake Superior basin and in the Red River basin are in places very thick, as at Wrenshall, but generally there is only a thin deposit of lacustrine sediment in the deep pools of these old lake beds and in certain localities there is only sand.

On the borders of the Lake Superior basin red boulder clay was deposited in large quantities; it is now dissected by steep gorges.

In addition to the great glacial lakes of the Lake Superior and Red River basins, there were numerous small lakes or ponded areas along the border of the ice, in which silt was deposited. Such an area lies north of Princeton at the large plants of Brickton and similar areas lie farther east along the northern border of a district which was occupied by a lobe of ice that extended northeastward from the Mississippi to the St. Croix Valley, above the Twin Cities. These clays were, in places, overridden by the later advances of the ice.

Recent.—Since the final disappearance of the Pleistocene glaciers there have been only slight modifications of the surface and very little accumulation of material or removal by erosion. A few lakes and swamps have been drained, and a few have been filled. The large river channels have been covered with silt.

GEOLOGICAL FORMATIONS YIELDING FOUNDRY SANDS, LOAMS, AND CLAYS

The Sioux quartzite formation.—The oldest geological formation of importance to the sand industry is the Sioux quartzite which belongs to the Upper Huronian group, in the Huronian system.

This quartzite is exposed at numerous places in the state but because of its hardness it is expensive to quarry and is of little service in foundry work except when crushed. This quartzite is extensively quarried at Courtland on the Minnesota River; in Nicollet County, sometimes called the New Ulm quartzite; also at Pipestone, Jasper, and Luverne in the southwest corner of the state, and at Sioux Falls, South Dakota, where it is known as the Sioux quartzite.

By reason of its extreme hardness, density, and toughness, this quartzite withstands attrition and abrasion to a remarkable degree and is much in demand as "pebbles" for ball mills. The quarries at Jasper supply the trade. The quartzite is cut into rectangular blocks about 3x3x4 inches, which are rounded to pebble shape by tumbling in revolving cylinders, and are shipped for use in ball mills.

The defective blocks and rubble of the quarry are crushed for concrete aggregate and for road material, and in the process of crushing more or less fine material results, which is screened out and sold as sand, the general texture of which is shown in the mechanical analyses Nos. 200, 205, and 207, Table XIV. This sand, screened to the proper size, should be very effective as a blast sand for foundry use and should be valuable also for refractory purposes as the following determination of the mineral composition shows[4]:

Quartz, (SiO_2), 96.3 %; Orthoclase ($KAl\ Si_3O_8$), 1.4 %
Zircon, ($Zr\ SiO_4$), .1 %; Hematite (Fe_2O_3), 2.2 %

It probably would not be feasible to crush the Sioux or New Ulm quartzite for fine screenings or sand, but where such screenings may be obtained as a by-product at a nominal cost they are worthy of consideration for foundry use both as refractory sand for furnace linings and as blast sand. It should be noted that it is quartzite of this type that is elsewhere crushed and used in the manufacture of "ganister" brick for furnace lining, a small amount of lime or other fluxing material being used to insure incipient fusion to bind the material when burned.

The Kettle River formation.—In the vicinity of Hinckley, Pine County, midway between St. Paul and Duluth there is a quartzitic sandstone known as the Kettle River or the Hinckley sandstone which underlies a considerable area. It is concealed by a thin mantle only of glacial drift and the streams of the region have uncovered it at numerous points. Kettle River has cut a narrow canyon through it 50 to 100 feet deep for a distance of several miles.

At the town of Sandstone, on Kettle River, extensive quarries have been opened in the formation, for the rock is a high-class building stone, and until a few years ago when concrete so largely replaced stone for structural purposes, was much in demand and has been used in numerous buildings in Minnesota, Iowa, Illinois, and South Dakota. Laboratory tests show that this Kettle River sandstone used as aggregate makes a superior concrete and there is at present a growing demand for it for this purpose so that the output of the quarries at present is largely crushed rock.

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[4] Bowles, O., *op. cit.*, p. 202.

In density this rock is about midway between the Sioux quartzite and ordinary sandstone. The cementing material is principally silica and the quartz grains of the original rock have to a large degree been enlarged by secondary quartz showing crystal faces. The rock, however, is still granular and upon crushing breaks along the faces of the grains instead of through the grains themselves. The screenings that result from crushing are more nearly true sand than are those from the Sioux quartzite, and a greater volume is obtained. These screenings are sold as sand and have been used for refractory purposes in the foundries of Minneapolis and St. Paul and in the steel furnaces of Duluth with satisfactory results. The subangular shape of the grains and their roughened surfaces offer good attachment for the bonding material which is an advantage for certain purposes. The comparative mesh of the sand, as shown by 185B, Table X, is 58, over 35 per cent being coarser than 60-mesh sand.

Chemical analyses of the Kettle River sandstone show the following composition:

	No. 1	No. 2
Silica, SiO_2	97.10	98.69
Alumina, Al_2O_3	2.20	1.06
Lime, CaO	.60	.42
Magnesia, MgO	.10	.01
Potash, K_2O		trace
Soda, Na_2O		.17
	100.00	100.35

No. 1. Analysis by United States arsenal, Watertown, Mass.
No. 2. Winchell, N. H. Geology of Minnesota, Vol. 1, p. 202. 1884.

The Jordan formation.—The Jordan formation which is the uppermost member of the Cambrian group underlies all of southeastern Minnesota, but being overlain by several younger formations, it is deeply buried in the greater part of the area and is known to be present only from the records of deep wells. Natural exposures of the formation are seen, however, along the northwest border of the area. There are exposures along the valley of the Minnesota River and along the Mississippi below Red Wing where such tributaries of the Mississippi as Zumbro and Rock rivers have cut into the Cambrian beds.

The only pits where the Jordan was being mined for sand on a commercial scale were found in the valley of Minnesota River in the vicinity of Ottawa and Kasota, Le Sueur County. The pits in these localities were one-half to one mile from the railroad stations and all are between the railroad and the river. Numerous other exposures where good sand might be obtained from the Jordan were seen between Ottawa and Merriam Junction, thirty miles to the northeast, but no pits had been opened. There was little inducement to open new pits because the pits at Ottawa and Kasota are almost ideally located. They are close to the railroad, have excellent drainage, and the banks of sand are 10 to 20 feet deep. The sand is so slightly coherent that a steam shovel might be operated without blasting. Sand could be produced there in practically unlimited quantities at a nominal cost per ton.

The southeastern part of the state in Wabasha, Winona, and Houston counties was not studied in sufficient detail to determine to what extent the Jordan is being used as a source of sand in this part of the state, or its availability.

The samples of Jordan sand, collected in Fillmore County at Preston and in Wabasha County at Mazeppa, were so similar in texture and mineral content to those collected from the Jordan sandstone in Le Sueur County that it was difficult to distinguish between them. These samples, together with field observations generally, serve to show that the Jordan is remarkably uniform in character over wide areas. Cursory examination showed it difficult to find anything but quartz in most of the samples. There can be little doubt that the Jordan furnishes sand as nearly pure quartz as any sand in the state. The formation which is 75 to 200 feet thick is not entirely uniform in character or in texture, but in all localities where good exposures of the formation were seen, beds 10 to 20 feet in thickness were found in which the sand was essentially pure quartz, with a texture such as shown in samples 8, 19, 170 etc., Table X.

The sand of the Jordan formation, in its coarser phases at least, which are preferred for foundry work, consists of quartz grains which in the larger sizes, i.e., the 20 and 40 mesh, are exceptionally well rounded; in fact occasional grains are found that are almost perfect spheres and even in the smaller sizes, i.e., 60 and 80 mesh, the grains are less angular than in average quartz sand.

Standard sand, known to the engineering testing laboratories throughout the country as Ottawa sand, comes from Ottawa, Illinois, and consists of essentially pure quartz sand sized to 20 mesh. Sand of this size screened from the Jordan sand from Ottawa, Minnesota, or from Merriam Junction can not be distinguished from the standard sand of Ottawa, Illinois.

Other sand formations occur in the Cambrian group in Minnesota in the Franconia and Dresbach formations, but in uniformity of texture, mineral content, and in availability they do not compare favorably with the Jordan sand.

The St. Peter formation.—The St. Peter formation appears in the geologic section about 200 feet above the Jordan formation and belongs to the next higher group or system, the Ordovician.

The St. Peter like the Jordan consists essentially of quartz sand. It is even more widespread than the Jordan, extending eastward and southward far beyond the boundries of Minnesota. It is rarely cemented sufficiently to be of value as building stone and is on the whole finer than the Jordan. Certain horizons in the St. Peter formation locally are as coarse as the Jordan, but rarely are such horizons thick enough to warrant separating them from the finer beds above and below.

In fresh exposures the St. Peter sand is usually very white and it has the appearance of exceptional purity but a bank sample of the material usually contains 1 to 2 per cent clay which is more than the Jordan carries. It also contains more silt than the Jordan.

For ordinary core work in foundries the St. Peter is very satisfactory, and since it constitutes the bed rock underlying the greater part of Minneapolis and St. Paul an ample supply of this sand is available in these cities. The St. Peter sand upon weathering takes on a yellow color due to iron staining and in this condition is sometimes preferred to the fresh white sand in foundry work. The preference for this type of sand is probably to be attributed to the slight roughing of the surface of the quartz grains by the deposit of iron oxide which affords a better attachment for the bonding material used.

In the region from St. Paul southward to Northfield, a distance of forty miles, the St. Peter formation is generally the bed rock. The glacial drift being thin in much of this area, numerous exposures of the St. Peter appear, usually as a soft yellow sand, or as friable sandstone. From Northfield eastward to the Mississippi along the valley of Cannon River the St. Peter formation is conspicuously exposed in the flanks of the flat topped, mesa-like hills and in the valley sides as white or yellow sand.

From Red Wing to the Iowa line the St. Peter is seen in the valleys tributary to the Mississippi at gradually lower and lower levels as one goes southward. The exposures are too numerous to warrant special description. The most characteristic feature of the sand is its uniformity in texture.

The Oneota and Shakopee dolomites, which occupy the interval between the Jordan and the St. Peter formations, also carry thin beds or lenses of sand or sandstone similar to the Jordan or to the St. Peter, but such beds are usually pocket-like and rarely of commercial importance, except very locally.

A chemical analysis[5] of the St. Peter sandstone from Fort Snelling is as follows:

Silica, SiO_2	97.67%
Alumina, Al_2O_3	1.31%
Lime, CaO	0.41%
Potash, K_2O	0.02%
Iron, Fe_2O_3	0.55%
Soda, Na_2O	0.15%

A bank sample of the St. Peter sand, such as is used in foundry work, would probably show a considerably lower silica content, but samples from selected horizons of the cleaner sand show a silica content of 98 per cent.

The Decorah formation.—The Platteville limestone, Decorah shale, Galena limestone, and Maquoketa shale formations overlie the St. Peter sandstone and occupy the upper part of the Ordovician group of beds. The Decorah shale is extensively used in different parts of the state for making brick, tile, and terra cotta. It is of minor importance as a source of clay for foundry use because of the rather large percentage of fluxes usually present.

The Cretaceous formation.—As explained in the foregoing geological history a long interval of subaerial erosion and weathering immediately preceded the Cretaceous period, during which time the old crystalline rocks were deeply decomposed, the sedimentary rocks disintegrated, and the limestones leached of their readily soluble constituents. The feldspars of the crystalline rocks were kaolinized and in turn leached of much of their more soluble lime and alkalies leaving semi-refractory clays as a residuary.

The Cretaceous sea encroaching upon the land found great quantities of soft and loose products of rock-weathering ready for redistribution, and accordingly the deposits of the Cretaceous period consist of a great variety of materials derived from the acid and basic crystalline rocks and from the sandstones, limestones, and shales of the sedimentary formations.

In re-working this material the Cretaceous sea in some areas accomplished a remarkably complete separation of the coarse and fine materials, depositing beds of dense fat clays in certain localities, or at certain horizons, and clean, well-assorted sands in others. In other areas the separation was less complete or very poor and the products of rock-weathering were redeposited as poorly assorted clays and sands, or as alternating thin beds or laminations of these materials.

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[5] Winchell, N. H., Geology of Minnesota Final Report, Vol. 1, p. 202, 1884.

The Cretaceous formation in general has suffered little alteration or induration since its deposition, so that the beds are still found in much the same condition as they were deposited. The sands are commonly loose, incoherent material, and friable sandstone. The argillaceous material appears as clays or soft shales.

The old rock floor on which the Cretaceous was deposited was marked in certain localities at least, by numerous small potholes and caves, in which the clays accumulated in the manner illustrated in Figure 1.

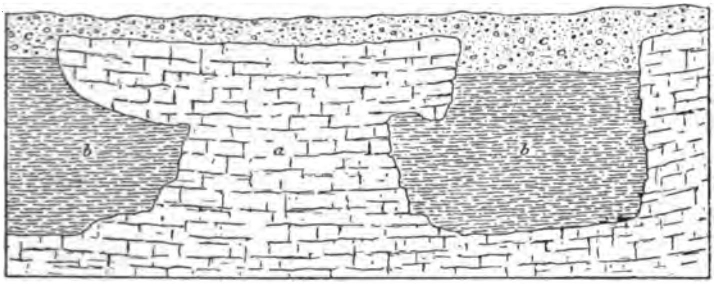

FIGURE 1. SECTION OF CRETACEOUS CLAY AT SOUTH BEND, (*a*) SHAKOPEE DOLOMITE; (*b*) CRETACEOUS CLAY; (*c*) DRIFT AFTER N. H. WINCHELL

One of the important deposits of foundry clay worked in the vicinity of Ottawa, Minnesota, occurs in these relations in potholes in the basal portion of the Oneota limestone, and in the top of the Jordan formation, samples of which appear in Table XIII.

One of the largest deposits of Cretaceous clay in the state, at present worked as a source of clay for the Red Wing potteries, is found in Goodhue County in the vicinity of Bellechester and Clay Bank. This clay has been used to a limited extent only in foundry work, but merits more extended use, since it is semi-refractory and certain beds in the series are highly plastic. The clay here occurs as thin beds for the most part alternating with beds of sand.

The sands of the Cretaceous frequently consist of nearly pure quartz, but such beds are usually thin, and there is also a considerable variation in texture in the different horizons. In view of the fact that much better sand for foundry purposes is obtainable from the St. Peter and the Jordan formations, the Cretaceous formation does not warrant special consideration as a source of quartz sand.

The Cretaceous formation is the source of the most refractory clay in the state. Chemical analyses of these clays show the following composition. The localities from which the foundry samples were collected are the same as for those given in the following tables.

TABLE II. ANALYSES OF BUFF TO WHITE BURNING CRETACEOUS SHALES

	1	2	3	4	5	6	7	8
Silica	69.92	69.84	68.298	69.050	59.72	70.10	87.70	68.70
Alumina	17.39	23.07	18.266	18.830	30.00	16.99	7.24	18.04
Ferric oxide Ferrous oxide	1.68	.48	2.867	2.607	......	Trace	Trace	1.53
Lime	.60	.11	.719	.296	.82	......	.67	1.24
Magnesia	1.11	.14	.802	.622	.51	......	.07	.56
Sodium oxide	.07	Trace	.81	1.066	......	......	3.17	.24
Potassium oxide	2.25		.60	1.461	......	10.69	.49	5.28
Phosphorus oxide	.....	.....	......	......	......	......	......	.09
Sulphur trioxide	.....	.....	....	......	......	.23	......	......
Titanium	.63	.....	......	......	......	......	......	......
Moisture	1.10	6.35	1.29	.898	10.34	1.98	Trace	1.40
Ignition	5.45	.....	6.155	4.912	......	......	Trace	......
Total	100.20	99.99	99.807	99.742	101.39	99.99	99.34	97.08

1. Red Wing, Goodhue County. Clay sampled at stoneware plant. F. F. Grout, analyst.

2. Red Wing, Goodhue County. Analysis reported by J. H. Rich to Heinrich Ries.

3. Red Wing clay. Sample from Minnesota Stoneware Co., Red Wing, April 22, 1902. C. P. Berkey, analyst.

4. Red Wing stoneware clay, air dried. C. P. Berkey, analyst.

5. Ottawa. Ottawa Brick Co. Ries, Heinrich, Clays; their occurrence, properties, and uses, 1906. 6, 7, and 8. Minnesota Geol. and Nat. Hist. Survey Final Rept., Vol. 1, p. 438, 1884.

6. Near Mankato. Clay filling hollows in Shakopee dolomite.

7. Near Mankato (sec. 20). White clayey bed of considerable extent.

8. Near Mankato. Clay or shale between Shakopee dolomite and Jordan sandstone in L'Huillier Mound.

TABLE III. ANALYSES OF RED-BURNING CRETACEOUS SHALES

	1	2	3	4
Silica	63.65	61.32	58.14	73.34
Alumina	17.27	12.27	19.40	14.75
Ferric oxide	....	3.62	5.52	5.45
Ferrous oxide	4.75	4.18	....	
Lime	1.21	.99	.79	.28
Magnesia	.06	1.76	1.52	.05
Soda	.91	.42	.54	Trace
Potash	2.47	3.59	2.09	Trace
Barium oxide	....	.05	....	....
Manganese oxide	....	.27	....	....
Phosphorus oxide	....	.27	....	....
Sulphur	....	.19	....	....
Titanium oxide	.62	.66	.68	....
Moisture	2.03	....	2.10	....
Loss on ignition	7.36	10.73	8.81	4.71
Total	100.33	100.32	99.59	98.58

1. Gray shale, west of Springfield. F. F. Grout, analyst.

2. New Ulm, Minn. Brick clay, U.S. Geol. Survey Bull. 60, p. 151, 1890. T. M. Chatard, analyst. A brick made from this clay is reddish brown, strongly sintered, somewhat fractured. Sample taken by John Lind on south bank of Cottonwood River on section line at river crossing, east of wagon-road crossing, south of New Ulm.

3. Clay sampled by A. Parker, of Brown Valley, Minn., just beyond the state line in South Dakota. F. F. Grout, analyst.

4. Red ochery clay, near Mankato. Minnesota Geol. and Nat. Hist. Survey Final Rept., Vol. 1, p. 438, 1884.

As explained elsewhere, however, in the description of the foundry loams, the Cretaceous beds frequently consist of an intimate mixture of nearly pure quartz sand and semi-refractory clay, the deposits at Bellechester being a case in point. For material of this type the Cretaceous merits consideration.

Glacial deposits.—From what has been said above it will be readily understood that the glacial deposits are extremely variable in character, physically, mineralogically, and chemically, therefore it is difficult to describe them briefly or to explain in what ways they are unsuited to certain purposes and well adapted to other purposes. In each of the succeeding periods of glaciation the ice picked up more or less of the older glacial material, mixed it with material newly derived, and redeposited it in great confusion.

With reference to the sands and foundry materials the glacial deposits of Minnesota may be grouped as follows: Moraines of Wisconsin drift from the north and northeast (red drift); moraines of Wisconsin from the northwest; outwash; and glacial lake deposits. These groups are based on differences in character and not strictly on origin, for example, the gray drift moraines include material deposited in two or three separate invasions of ice.

Moraine deposits.—Where the ice held its position for considerable time, the deposits laid down at the edge of the ice sheet are called moraines. These were deposited by the ice directly. Their topography is distinctive. The surface is characterized by sharp knolls and enclosed basins, by hillocks, and hollows, or by interrupted ridges and troughs, which may interlock in places and assume rudely parallel positions. The depressions are often without outlets and water falling into them forms marshes, ponds, and lakes where the material constituting their bottoms is sufficiently impervious to prevent its escape. The knolls vary in size, but are usually rounded at the top and have moderate to steep slopes. Variations in height of moraines are due to the unequal amount of material held by the ice at those points. The moraines are arranged in rudely concentric lines which mark successive positions of the border of each ice sheet as it was melted off from that region. For building and foundry purposes, it is only the "sandy moraines" that contain deposits of value.

Ice advanced over Minnesota from two directions. One lobe of the glacier came from the north and northeast, from the Lake Superior region and northern Wisconsin, traveling over rocks of the siliceous type, largely sandstones, quartzites, and crystalline rocks. The material brought to Minnesota by this lobe of the continental ice sheet was predominantly sandy and such clay as it contained carried relatively small amounts of fluxes such as lime, soda, and potash. This material is known as the "red drift," considerable deposits of which occur along the eastern side of the state, from Minneapolis and St. Paul north. By careful selection material may be found in this red drift well suited for use as sand. Some is used for foundry work at Minneapolis. See Table XII, No. 254.

The other lobe of the glacier coming from the west and northwest brought much more limestone, clay, and shale—the gray drift. The deposits of sand are relatively few and impure. There is little material that can be used for foundry work.

Glacial loams.—Some of the loams in Minnesota are derived from moraine material. In creeping slowly over the region the glacial ice, 1,000 feet or more in thickness, with great quantities of rock incorporated in it, developed much movement within the mass itself. It served as a great mill in which the rock fragments were ground upon each other, much of the rock being reduced to fine silty material which has aptly been called "rock flour." During the warmer seasons of the year in glacial time, great streams issued from the ice margin carrying large quantities of this rock flour which was spread over the flood plains. During the colder seasons, with the diminishing of the flood waters, this silty rock flour became dry dust which was blown about by the winds and some of it was carried back over the glacier's margin and deposited on the surface of the ice itself. When the ice ceased to move and finally disappeared by melting, this silty rock flour was gradually let down and left as a blanket mantling itself indiscriminately over the knolls, hills, and intervening low areas of the terminal moraine, as well as over the ground moraine.

This silty rock flour was derived in part from the grinding up of partially decomposed feldspars, argillaceous limestones, and siliceous dolomites susceptible of further decomposition. Later, under the influence of superficial weathering, decomposition and leaching took place carrying away much of the soluble matter and leaving behind the more insoluble clay residuum, thereby changing the rock flour from a silty to a loamy consistency. More or less of the loams in Minnesota that are used in foundry work were derived in this manner. These loam deposits are variable in depth, in texture, in clay content, and in content of other minerals, and are irregular in distribution. A product uniform in character is hardly to be expected from this source, and an attempt to map these loams except in a very general way would encounter many perplexing problems.

Outwash deposits.—As the ice melted the water issuing from the edge of the glacial ice carried with it sand and gravel. These were spread over the plains in the form of alluvial fans. As the escaping waters continued to deposit sand and gravel, these fans united and formed outwash plains. The outwash plains lie on the outer border of the moraines, and the sand and gravel composing them is sorted by the action of the escaping waters. Many outwash deposits may be traced up to a moraine, which marks the position of the ice border when they were laid down. Some show a decrease in coarseness passing away from the moraine, the coarse material having been dropped close to the edge of the ice and the fine carried a greater distance.

The waters found themselves in valleys, over which they spread. Carrying loads too great for their velocity, they aggraded their valleys and built up large valley trains. At the maximum of their discharge, the outwash deposits consisted of sand and gravel. They extend far beyond the unstratified drift with which they are associated. They supply by far the greater portion of the sands used for structural work in Minnesota, and also much foundry material.

A type of loam differing slightly from that formed in the weathering of sandy moraines is derived from the sandy flood plains of glacial streams. Probably the broad flood plains supported some vegetation and received deposits of sand and rock flour only at time of flood; so that the sand is mixed with vegetation as well as partly weathered. Some such deposits of loam are many feet thick. By reason of their mode of formation, they are likely to be more uniform in composition and depth than the loams of morainic deposits. This type of loam is therefore most promising for foundry material.

The loam on the old flood plains has been subjected to the same process of superficial weathering as the moraines; that is, it has decomposed and leached to some extent, as a result of which the upper one to three feet is frequently heavier, or more clayey, than that below, which must be taken into account in pitting it for foundry use.

Much of the loam referred to underlies good agricultural land. It is possible to recover the loam without destroying the soil. If the upper portion of soil is moved by wheel scrapers and spread again over the floor of the pit after the foundry loam is removed, the land is still of full value for agricultural purposes. Loam can be removed in this way at a very low cost without injury to farm lands. A similar method has been used in the Red River Valley in working some clay deposits. The method is employed in New Jersey to win foundry loams of exactly the type here described.

The sands above described as occurring on glacial flood plains do not all border streams at present, for the streams that built these ancient plains in many instances became extinct with the glacier. The old flood plains are not infrequently far removed from present drainage lines, or if they are near present drainage, they may or they may not bear definite relation to present drainage.

Lake beaches.—In the northwest part of the state, in the region of glacial Lake Agassiz, there is a shortage of all kinds of sands. The sands of this region are secured from ridges of sandy gravel formed along the shores of extinct lakes at successively lower levels, down to existing lakes. These ridges are known as "lake beaches," and are the result of sorting by wave action.

Loess.—In the southeastern part of Minnesota from the vicinity of Red Wing to the Iowa line there is a belt of country bordering the Mississippi River about 30 miles wide and 100 miles long, in which a fine silty loam known as loess occurs at many places. The distribution of the loess is shown in a general way in Figure 2.

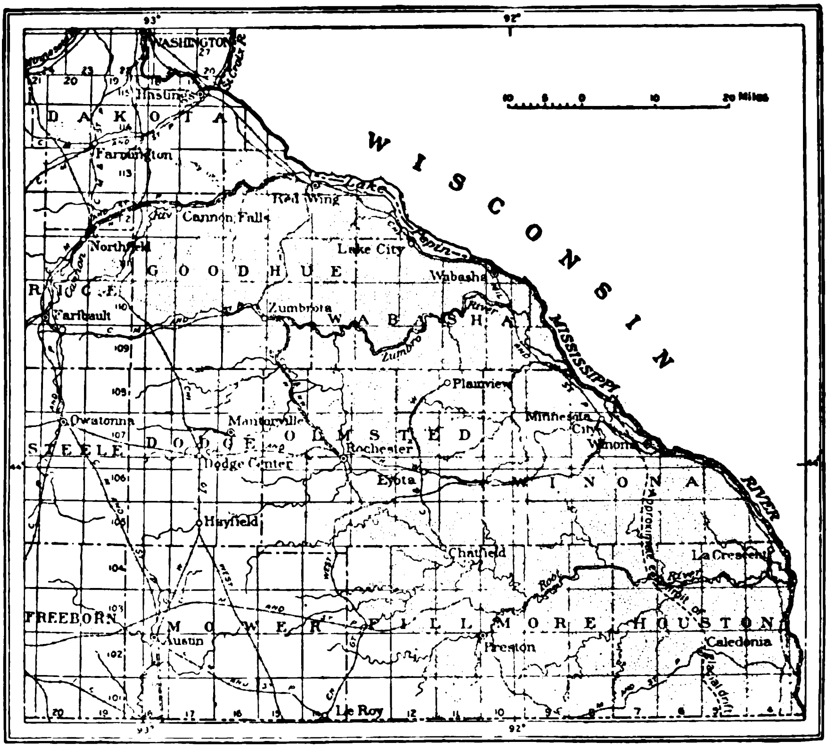

FIGURE 2. MAP OF SOUTHEASTERN MINNESOTA SHOWING AN AREA (DOTTED) IN WHICH THE DRIFT IS LARGELY COVERED WITH LOESS. THE LOESS MANTLE IS NEARLY CONTINUOUS EXCEPT ALONG THE LARGER VALLEYS AFTER FRANK LEVERETT

The loess is of interest to the founding industry as a source of molding sand for brass, other alloys of copper, aluminum, etc. Most of the brass sand imported by the foundries of Minnesota from Missouri, Illinois, and Kentucky is simply loess such as may be had in southeastern Minnesota at hundreds of places.

The loess occurs in the area shown in Figure 2 up to 40 feet in depth, and possibly deeper. It is not limited by any altitudes in this area, but occurs capping the highest hills, bluffs, ridges, and uplands 500 feet or more above the Mississippi, as well as in the valleys down practically to the river level. A typical example of loess is to be seen at Red Wing capping Barn's Bluff which is a small isolated hill rising with abrupt slopes, and sheer cliffs to about 400 feet above the river. The oess, at least 20 feet in depth, caps the highest part of this hill. It occurs also in the vicinity of Red Wing mantling the terraces 40 feet above the Mississippi and back from the main stream in the side valleys at all levels to points 400 feet above the river.

Some of the loess at low levels has been derived from the upland loess and washed down by streams, but part of it was originally deposited at the lower elevations.

On the whole the loess on the uplands 200 to 500 feet above the Mississippi is more uniform in texture and mineral composition than the loess in the valleys. In deep fresh exposures the loess is usually pale blue-gray in the lower portion, pale yellowish gray in the middle portion, and brown or yellowish brown in the upper one to three feet. There is an appreciable difference usually in the texture of the material accompanying the difference in coloring; that is, the basal portion of bluish tint is more silty, the central portion more loamy, and the surface portion clayey. The difference in coloring and texture appears to be due to progressive weathering rather than to a difference in the original deposition.

Owing to the great abundance of the material and its accessibility to the railroads it is unnecessary to describe in detail the numerous exposures. At Clay Bank station, south of Red Wing, the Chicago Great Western Railroad has made a cut about 8 feet deep through the loess and the material could be loaded there with steam shovel. Other deposits of the same material similarly situated with reference to railroads could no doubt be found so that for foundry needs a practically unlimited supply can be had at nominal cost.

The following analysis shows that the loess carries about 13 per cent of iron, alkali, and alkali earth compounds, which would insure a low fusion point, but since the temperatures of the melts of brass and its alloys are low there is no danger of fusion of the loess when used as molding sand for these metals.

The texture of the loess is indicated by the mechanical analyses of Table XI. A chemical analysis is stated below:

CHEMICAL ANALYSIS OF LOESS (BY F. F. GROUT)

Silica	71.53
Alumina	8.07
Iron oxide	5.63
Magnesia	1.74
Lime	2.36
Soda	1.85
Potash	1.97
Ignition	4.50
Water	2.30
Titanium oxide	.31
	100.26

As to the origin of the loess there has been much difference of opinion, some investigators claiming a wind origin and others a water origin. Probably both agencies have been active. Undoubted evidence of water stratification in the loess is to be seen in certain localities even on the uplands 500 feet above the Mississippi River; and at other localities equally conclusive evidence of wind work is to be found. There has, no doubt, been more or less redistribution of the loess by both wind and water since its original deposition.

The glacial rock flour, above described, may have been the chief source of the loess, but the fact that the impure dolomites of the region upon weathering leave a residuary product of closely similar constitution suggests that this also may have been a source.

Recent deposits.—The sands of the recent period used in Minnesota belong to two classes, lake sand and river sand. Most of the lake sand can be used for building purposes, and may be used in some foundry work. An extensive plant is operating at Duluth where the sand is obtained from Lake Superior.

A type of loam is found mantling the terraces in the valleys of streams at levels of 20 to 200 feet above present streams. In mode of origin these loams are not unlike the glacial outwash loams. In fact some of them are genetically the same. Others, however, were formed in a similar manner but at a later peroid; that is, they were deposited by the streams that in postglacial time have passed through the stages of aggradation and degradation. Generally these loams are variable in character, but afford good foundry material if sufficient care is exercised in choosing the localities and in pitting the material.

TABLE IV. LIST OF MINNESOTA FOUNDRIES AND LOCALITIES SUPPLYING THEM WITH FOUNDRY SAND

	Brass Sand	Molding Sand	Core Sand
Albert Lea			
American Gas Machine Co.		Outside state	St. Peter, Minneapolis
Austin			
Austin Foundry		Lime Springs, Ia.	Local
Brainerd			
Parker and Topping Co.		Kerrick	Coarse, local
		St. Paul	Fine, St. Peter, Minneapolis
Chaska			
Ess Bros.		Minneapolis	Minneapolis
Cloquet			
Cloquet Foundry		Local	Local
Crookston			
Crookston Iron Works		Kerrick	Local, glacial
Duluth			
Clyde Iron Works		Kerrick	Fine, St. Peter, St. Paul
			Coarse, Lake Superior
Duluth Brass Works		Whitehead Bros., Buffalo, N. Y.	Whitehead Bros., Buffalo, N. Y.
Duluth Foundry and Faucet Co.		Albany sand	
Duluth Iron Works	Local	Kerrick	Coarse, Lake Superior
			Fine, St. Peter, St. Paul
Minnesota Radiator Co.		St. Paul	Lake Superior
National Iron Company		Kerrick	St. Peter, St. Paul
Fairmont			
Fairmont Gas Engine Co.		Waterloo, Ia.	St. Paul
Faribault			
Faribault Machine Shop		Local	St. Peter, local
Winter and Co.		Local	St. Peter, local
Nutting Truck Co.		Local	St. Peter, local
Fergus Falls			
Fergus Falls Iron Works		St. Paul, Kerrick	Local, glacial
Hibbing			
Oliver Mining Co.	Chicago	St. Paul	Local, glacial
La Crescent			
Smith Grubber Co.		Local	Local
Lake City			
Gillett-Eaton and Squire Co.		Local	Local
Mankato			
Little Giant Co.		Local	St. Peter, local
Mankato Mfg. Co.		Local	St. Peter, local
New Prague			
New Prague Foundry Co.		Mankato	Mankato, St. Peter
Ortonville			
Ortonville Foundry		Big Stone City, S. D.	Local, glacial
Owatonna			
New Owatonna Mfg. Co.		Faribault	St. Peter, Faribault
North Star Iron Works		St. Paul	St. Peter, Faribault
Paynesville			
C. W. Peavey		Local	Local, glacial
Red Wing			
Red Wing Iron Works		Local	Local
St. Cloud			
Granite City Iron Works		Minneapolis	St. Peter, St. Paul
St. Cloud Iron Works		Kerrick	St. Peter, St. Paul

TABLE IV—*Continued*

	Brass Sand	Molding Sand	Core Sand
Thief River Falls			
Thief River Falls Iron Works		St. Paul, Kerrick	Local
Virginia			
Virginia Foundry Co.		Kerrick	Biwabic, glacial
Winona			
Gate City Iron Works		LaCrosse, Wis.	Minneapolis
New Winona Mfg. Co.		Rockford, Ill. Minnesota City	River, local
Winona Machinery and Foundry Co.		Minneapolis	Jordan, Ottawa
Minneapolis			
American Brake Shoe Co.		Local, glacial	
Crown Iron Works		Local, glacial	
Commutator Co.	Albany, N. Y.		St. Peter, local
Eagle Foundry		Local, glacial	Glacial, local
Flour City Ornamental Iron Co.	Milwaukee, Wis. France		St. Peter, local
Gas Traction Foundry	St. Louis, Mo.	Local, glacial	Steel, Jordan, Ottawa
Mpls. Steel and Mach. Co.		Local, glacial	
Soo Line Railroad Shops	Albany, N. Y.		St. Peter, local
University of Minnesota Foundry	Albany, N. Y.	Local, glacial	St. Peter, local
St. Paul			
American Hoist and Derrick Foundry	Albany, N. Y.	Local, glacial	Steel, Ottawa St. Peter, local
Herzog Foundry	Local, glacial		
Northern Malleable Iron Works	St. Louis, Mo. Fort Snelling		
Union Brass Works	Monmouth, Ill.		
Valley Iron Works		Local, glacial	
St. Paul Foundry Co.		Local	

LABORATORY METHODS OF TESTING FOUNDRY SANDS, LOAMS, AND CLAYS

Mechanical analysis of sands, loams, and clays.—The mechanical analysis of a sand or loam, as generally understood, consists simply in separating the material into a series of products graded according to size of the grains and weighing these products to determine the percentage of the coarse and the fine material present. There are many ways of sizing, but most of those in general use are modifications of two well-known methods: (1) by using a set of screens, in which the material is separated dry into a series of products ranging from coarse to fine, and (2) by the use of water so that the different sized grains in the material are separated from each other by their buoyancy. The former is commonly called the dry method, and the latter the wet method. The two methods are frequently combined and there is almost no limit to the degree of refinement to which either method may be carried.

The sizing of sands by means of a set of screen sieves is employed universally where sands are used in the various industries and the value of a given sand, or its adaptability for a certain purpose, is based to a greater or lesser degree on the results shown by the screen analysis.

The dry screen analyses of the molding sands were made in the ordinary way, using a set of standard 6-inch screen sieves of 4, 10, 20, 30, 40, 50, 60, 80, 100, and 200 meshes to the inch. The 30- and 50-mesh screens were used only in special cases. The sand samples for analysis, consisting of 50 grams (about 2 ounces), were previously dried in a sand bath at a temperature of 100° C. for 24 to 48 hours, or until they eased to lose weight, after which the samples were pulverized in an iron mortar with a rubber shod pestle to break up the clusters without breaking the individual sand grains. The screens were shaken by hand, using, one, two, or more screens at a time, as conditions warranted. In some instances a small stiff bristle brush was used on the screens to hasten the passage of the sand through the screen, since with some samples no reasonable amount of shaking or jarring would pass the sand without the aid of a brush. A mechanical shaker operated by an electric motor was tried, but found impracticable, since uniform or complete separations generally could not be obtained.

The screens were calibrated in the physics laboratory of the University of Minnesota by the aid of an optical micrometer, with the results shown in Table V.

TABLE V. SIZE OF SCREEN OPENINGS AND DIAMETER OF WIRE IN SCREENS

Mesh of Screen	Diameter in Inches of Wire in Screens According to Manufacturer	Size in Inches of Opening of Screens According to Manufacturer	Size in Inches of Opening of Screens Found by Actual Measurement
4	.065	.185	.185
10	.035	.065	.074
20	.0172	.0328	.0341
30	.0135	.0198	
40	.01	.015	.0189
60	.008	.0087	.0096
80	.0057	.0068	.0074
100	.0045	.0055	.0062
200	.0021	.0029	.0038
220	.0017	.0028	
240	.0016	.0026	
260	.0016	.0022	
280	.0016	.002	
300	.0016	.0017	

In ordinary sands the grains are more or less coated by a film of clay which in the fine sizes materially increases the actual diameter of the grains. In sands where silty material is present in appreciable amounts together with 2 to 10 per cent of clay, the silt grains are cemented to the coarser grains of sand by the clay film in greater or less amounts which still further increases the actual diameter of the sand grains. Both the silts and the finer sizes of sand are gathered in clusters, or compound grains, particularly in loamy sands, and these clusters function as unit masses, and in the ordinary screen analysis appear as individual grains in the various sizes.

The purpose of pestling dry sand is to break up these clusters, free the sand grains from adhering finer material, and bring the material into a state of individual particles. In some sands, and in loams generally, however, no ordinary amount of pestling in the dry state will completely break up the clusters or remove the adhering silt grains, much less will pestling remove the clay coating from the grains of sand. Hence it is impossible to obtain a true sizing of the material by the dry method. The common screen analysis, while valuable because easily made and because it shows in a general way the physical constitution or texture of the sand, is at best a proximate analysis only.

Inasmuch as clay in molding sand performs an important function as bonding material, it is essential that a determination as accurate as possible be made of the clay present in the different molding sands, and accordingly the following procedure, adapted from one of the common methods of soil analysis, was employed.

A 50-gram sample of the sand to be tested was taken in the same manner as for a dry screen analysis; that is, the sample was weighed out after thorough drying in the sand bath. The sample was transferred to a common 8-ounce nursing bottle. Six ounces of distilled water and 5 cubic centimeters (about one teaspoonful) of ammonia, were added, making the bottle about half full. The bottle was placed horizontally in a mechanical shaker, shown in Figure 3, and shaken for five hours; the purpose being to free the sand grains of any coating of clay and to deflocculate the clay.

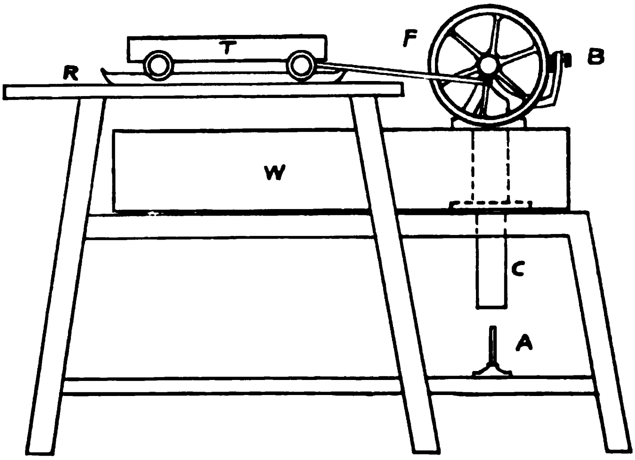

FIGURE 3. HOT AIR ENGINE USED FOR SHAKING BOTTLES IN CLAY DETERMINATIONS

The shaker was propelled by a small hot air engine. The cylinder *C* about 2 inches in diameter by 12 inches long, was thin walled. The upper part was surrounded by a tank of water *W* to prevent excessive heating. Heat was supplied at the lower end by a Bunsen burner *A*, the amount of heat being controlled by the supply of gas, this in turn determining the speed of the engine. The engine would run for hours without attention. The length of stroke of the engine piston was about 2 inches. The tray *T* carried 12 bottles and moved horizontally on the track *R*. The flywheel *F* ran about 40 revolutions per minute. The length of stroke of the pitman from the flywheel to the tray was about 3 inches.

Immediately after shaking, the contents were washed into graduated glass cylinders about 13 inches tall and 1⅞ inches in diameter which were allowed to stand at room temperature for 24 hours. The material that remained in suspension after 24 hours was considered clay. The water with clay in suspension was siphoned off into large beakers, after which the sand in the cylinder was again agitated by jetting distilled water under pressure into the sand; then the cylinders were allowed to stand again for 24 hours. This process was repeated until the cylinders showed nothing in suspension on standing for 24 hours.

The material obtained from these 24-hour decantations, designated clay, was precipitated in the beakers by adding a small amount of barium chloride, for in most cases the clay would not settle out completely by gravity. This clay was recovered, dried, and weighed, thus giving the percentage of clay in the sample which might be regarded as acting as the bond for molding purposes.

The contents of the cylinders, after removing the clay, were again agitated with distilled water and allowed to stand for 30 minutes. The water, with what was in suspension, was siphoned off, or decanted, at the end of 30 minutes, this process being repeated until nothing remained in suspension for the 30-minute period. The material from these 30-minute decantations, called "thirty minute silt," was recovered, dried, and weighed.

In the same manner a 15-minute silt was separated, recovered, dried, and weighed, after which the contents of the cylinders, regarded as true sand, were recovered, dried, and weighed, and then subjected to the usual mechanical dry screen analysis, using the screen sieves.

This combination of wet and dry methods of analysis shows the percentages of clay, 30-minute silt and 15-minute silt, present in the sample and the percentage of 4, 10, 20, 40, 60, 80, 100, and 200-mesh sand present after removing the clay and silts, making 11 separates in all.

In the course of the laboratory work on foundry sands, 320 samples of sand, loam, and clay were subjected to the common screen analysis, following the dry method above described. Two hundred sixteen of these samples were subjected to the combined wet and dry method of analysis. In the various tables where the results of these analyses are recorded, the dry method analyses are referred to as "A" and the analyses by the combined method, showing the percentage of clay and silt, are referred to as analyses "B."

Comparison of wet and dry methods of analysis.—A comparison of the results of these two methods of analysis of the same materials brings out many facts in connection with the texture of sands. Illustrating the marked difference in results by the two methods, the results of analyses of three samples, 9, 3, and 18 are given in which analysis "A" and "B" in each are duplicate samples of the same material. These examples are fairly representative of the entire series.

TABLE VI

Mesh of Screen	Sand No. 9		Sand No. 3		Sand No. 18	
	A	B	A	B	A	B
4— 10			.20		1.00	.20
10— 20	.80	.74	.82	.86	.20	.30
20— 40	43.50	22.80	6.63	5.74	.70	.60
40— 60	29.00	26.06	18.34	14.10	1.00	.54
60— 80	17.00	25.08	6.20	6.08	1.50	2.32
80—100	4.50	10.00	4.64	4.22	6.00	3.38
100—200	1.00	7.44	16.90	10.98	29.70	22.82
200-silt	2.00	3.50	43.32	38.00	59.50	53.48
15-minute silt		.12		2.00		1.90
30-minute silt		1.40		6.00		7.00
Clay		2.00		10.80		7.00
Total	97.80	99.14	97.05	98.78	99.60	99.54

Sample 9 is a quartz fire sand, 3 is a common loam, and 18 is a brass sand. Notwithstanding all the samples for analyses "A" were thoroughly pestled, there still remained clusters or aggregates of grains that did not break up into individual particles. These clusters did break up by treatment with ammonia in the analyses "B."

It is to be noted that different sands and loams behave very differently with respect to the clustered grains; that is, some samples yield to pestling readily while others do not, so that there is no uniformity in results, thus the sizing obtained by the dry method of analysis is not to be depended on even in sands with a small clay content, as sample 9 shows.

The primary purpose in the wet method analysis was to determine the percentage of clay present in the various sands, loams, and so-called clays used in foundry work, the assumption being that such clay afforded the bond essential to molding sand. But this method of analysis also provides two silt determinations; that is the 15-minute and 30-minute silt, the grains of which are intermediate in size between the 200-mesh screen and the clay. Such experiments as were undertaken indicate that these silts play an important rôle in the permeability of the sand by their behavior in granulation. They are important also in connection with the tensile strength developed in the molds, both in the green and in the dry sand.

Perfect sizing was not attained in the wet analysis "B" because the method employed involved two essentially different principles in the separation. That is, the silt separations relied on the suspension of the particles in water, which in turn depended on the specific gravity of the individual particles and not on their mass or diameter, whereas the sizing of the sand after the silts and clays were removed, using the sieves, depended on the diameter of the grains only.

As a check on the method of sizing, the silts obtained in the analyses "B" were examined under a microscope, using a scale to measure the diameter of the silt grains. While, as was anticipated, many large grains were found in the silts, some even larger than the openings in the 200-mesh screen, still the percentage of such grains was small, and the bulk of the material, both in the 15- and the 30-minute silt, was fairly uniform in size. These measurements showed that the average diameter of the grains in the 15-minute silt was .00053 inch and the average diameter of the grains in the 30-minute silt was .000236 inch. That is, the diameter of the 30-minute silt grains was a little less than half that of the 15-minute silt, indicating a fair degree of sizing by water suspension.

The openings in the 200-mesh screen, as shown in Table V, were .0038 inch; and while no attempt was made to measure, or otherwise determine the size of the clay grains, numerous workers in soil analysis have given the diameter of clay grains as "under .000197 inch." From which it will be seen that there is a rather wide interval between 200-mesh sand and clay, of which heretofore no account has been taken in ordinary molding sand analyses. The determination of the percentage of 30-minute and 15-minute silts present in the various materials makes possible a more critical comparison of the samples as to their texture and permeability.

Comparing analyses.—To facilitate comparison of analyses a factor was sought that would express in a general way the comparative fineness of the individual sample as indicated by the screen analyses. Such a factor is recorded in the tabulated analyses.

The diameter of the sand grains in any of the separates obtained by screening naturally varies from the size of the opening of the screen through which the sand passes to the size of the opening of the next finer screen on which the sand is caught. The average grain in each of the separates may be taken as the mean between the openings. For example, the openings in the 40-mesh screen were found to be .0189 inch and the openings in the next finer screen, viz., 60-mesh, .0096 inch. The mean between these two is .01425 inch and the average or mean sized grain of the 40- to 60-mesh sized sand is taken to be .01425 inch in diameter. Determining the mean or average diameter of the other separates in the same manner gave the results shown in the following table.

TABLE VII

Mesh of Screen Used in Sizing Sands	Average Diameter of Sand Grains in Sized Sands
4—10	.1295 inch
10—20	.054
20—40	.0265
40—60	.01425
60—80	.0085
80—100	.0068
100—200	.0050
200-silt	.00216
15-minute silt	.00053
30-minute silt	.000236
Clay—below	.000197

The diameters of the 15- and 30-minute silts were determined by measuring the silt grains themselves with a microscope. The diameter of the clay grains was taken from tables published by workers in soil analysis.

The method of computing the fineness factor, or comparative grain, was to multiply the average diameter of the grain in each separate by the percentage of the separate present in the sample and divide the sum of the products so obtained by the sum of the percentages of the several separates.

For example, brass sand 18, taken from Table XI, computed for grain and mesh, gives the following results:

TABLE VIII

Mesh of Screen	Average Diameter of Sand Grain in Each Separate		Proportion of Each Separate Present		Product of Per Cent Multiplied by Average Diameter of Grain
4— 10	.1295	×	.002	=	.000259
10— 20	.054	×	.003	=	.000162
20— 40	.0265	×	.006	=	.000159
40— 60	.01425	×	.0054	=	.000076
60— 80	.0085	×	.0232	=	.000197
80—100	.0068	×	.0338	=	.000229
100—200	.0050	×	.2282	=	.001141
200-silt	.002165	×	.5348	=	.001157
15-minute silt	.00053	×	.019	=	.000010
30-minute silt	.000236	×	.07	=	.000016
Clay	.000197	×	.07	=	.000014
			.9954		.003420

$\frac{.003420}{.9954}$ = .0034 inch, the comparative diameter of grain. The comparative mesh computed by this method is an approximation only. Greater accuracy would have been obtained if the number of grains of sand in a unit volume for the different separates had been computed and used as a factor in computing the comparative mesh.

The comparative mesh was obtained by interpolating the comparative diameter of grain in the scale of screen openings given in Table V (page 33). Interpolating .0034 inch in the scale of screen openings, it was found to correspond to a mesh of 216 (see Fig. 13). Accordingly 216 is taken as the comparative mesh of this sand.

Laboratory tests for bonding power of sands, loams, and clays.—In testing the bonding power of molding sands the usual method employed in testing cement for tensile strength was used. This consists in making a briquet of the material to be tested having a cross section of one square inch in the center and larger at the ends, as illustrated in Figure 4, *A*, *B*, and *C*. The briquets were broken in the apparatus, Figure 5, by applying a load at the lower end of the briquet and measuring the stress, in pounds or ounces, required to break the one-square-inch section. The results give the tensile strength of the molding sand in pounds per square inch. In making the briquets the molds, shown in Figure 4, were used and the molding sand was rammed into them, following the approved methods

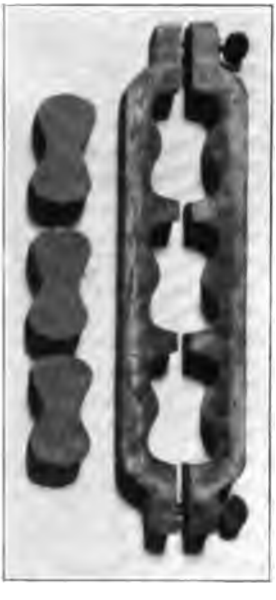

FIGURE 4. BRASS MOLD FOR MOLDING SAND BRIQUETS FOR TENSILE STRENGTH TESTS

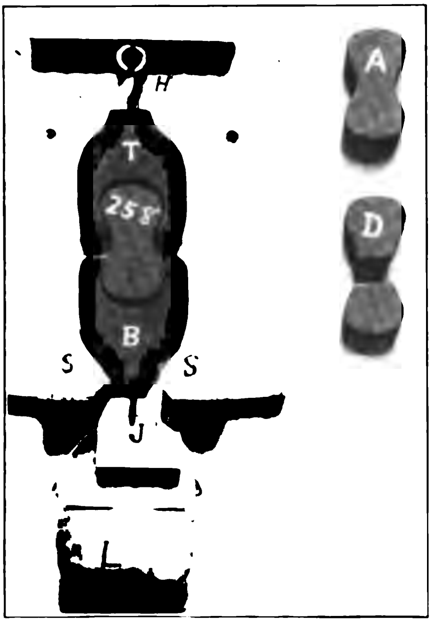

FIGURE 5. APPARATUS FOR BREAKING BRIQUETS OF MOLDING SAND TO DETERMINE TENSILE STRENGTH

of foundry practice in tempering the sand and tamping it into the mold.

The briquets were run in series of three, designated series A, B, and C, with three briquets in each series. The three briquets in series A were broken at once upon taking them from the molds to determine the tensile strength of the damp or green sand, taking the average of the three tests. The three briquets in series B were allowed to stand in the open air 24 to 48 hours for room drying, after which they were broken to determine the tensile strength of sand comparable to that of air-dried molds in foundry practice. The three briquets in series C were kiln dried, or furnace burned, as circumstances might suggest, at temperatures ranging from 400° C. (752° F.) to 1000° C. (1832° F.) after which they were broken and tensile strength noted.

In view of the fact that green molding sand rarely develops a tensile strength of more than a few ounces to the square inch, whereas the machines for testing cement briquets are not sensitive to such light loads, it was obvious that these machines could not be used for breaking the molding sand briquets, so special apparatus had to be devised for that purpose. A pair of jaws (Figure 5 *T* and *B*) were made of mahogany and provided with a mounting so that the briquets could be suspended vertically and the load applied directly to the lower end. This apparatus was sensitive to a breaking load of 2 ounces and gave satisfactory results up to loads of 100 pounds.

The upper jaw was suspended at *H*, by means of a hook and eye, and the lower jaw was carried by the briquet itself; thus forming a couplet that swung free and eliminated all torsional stresses. A bucket *L* was suspended on the hook *J* to receive the load, which consisted of water that was run into the bucket *L* by means of a rubber tube and pinchcock.

In measuring the breaking load everything below the breakline was counted; that is, the bucket *L* with its contents, the lower jaw *B*, and the lower half of the briquet carried by the jaw *B* were weighed and counted as breaking load. The blocks *SS* served to catch the jaw *B* when the break occurred so that there was no loss by spilling the water.

Green briquets weighed from 95 to 120 grams, or about 3 to 4 ounces, and in this method of testing the strength, about half of the weight of the briquet itself, was counted as initial load, and this was the measure of the sensitiveness of the apparatus; that is, if the briquet broke of its own weight its breaking strength was figured as one half of the weight of the briquet itself, or something less than two ounces.

For heavier loads larger buckets were used in the place of bucket *L* and bird shot, such as is used in ordinary cement briquet-breaking machines, was employed as load.

Determining the porosity of foundry sands and loams.—By porosity of a sand is meant the voids or interstitial space between the sand grains or the granules. It is the space unoccupied by solid matter, but occupied by air or water. The porosity of a sand is usually expressed in percentages of the volume of the mass. If a sand has a porosity of 30 per cent, it means that the sand grains occupy only 70 per cent of the actual volume of the container, and the remaining 30 per cent is vacant space or is occupied by air.

The test for porosity of the sands consisted in comparing the weight of a standard volume of each sample with the weight of the same volume of solid non-porous rock.

The standard volume used in the porosity tests was a brass cylinder 3 inches deep by 2 13/32 inches in diameter (Fig. 6 *V*), which was obtained by cutting a section from standard rolled brass tubing. This volume of water at ordinary room temperature weighed 228 grams. The average specific gravity of the rocks of the earth is 2.6 to 2.7. Ordinary molding sand is simply the fragments and weathered products of such rocks, and the numerous determinations made by many independent workers in soils and cement, and investigators of rock-weathering, show that common sand has a specific gravity essentially the same as average rock, viz., 2.65. The variations in specific gravity for the different types of sand are so slight as to be negligible. The specific gravity of the "fines" is slightly higher than for the coarse constituents, so that we have assumed a specific gravity of 2.7 as probably as near the truth as it would be possible to get even if precise determinations had been made. Multiplying 228, the weight of the standard volume of water, by 2.7 gives 615.6 grams as the weight of this standard volume of non-porous rock.

The standard volume brass cylinder was filled in turn with each of the sands after they had been dried in the sand bath for 24 hours, and a standard method of jarring the cylinder was used to compact the sand, following the method described by King.[6]

In making the porosity tests on molding sand the method of King was modified slightly as follows: A section of brass tubing (Fig. 6 *D*) the same diameter as the cup (Fig. 6 *V*) and 1½ inches high, was placed on top of the cup, held in position by a band. This section was filled with sand, thus adding a head of 1½ inches to the receptacle. It was found that more uniform results could be obtained in compacting the sand by this means.

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[6] King, F. H. Principles and conditions of the movements of ground water: Nineteenth Annual Rept. U.S. Geol. Survey, 2, p. 208, 1899. Some of the preliminary laboratory work in determining the porosity and permeability of the sands discussed in the treatise above mentioned was done by the writer in 1897 under the direction of Professor King.

The method of compacting the loose sand, as described by King, consists in holding the cup filled with sand firmly on a rigid table, preferably a stone slab, with one hand, and jarring the cup with the other hand by tapping it with a piece of wood, turning the cup part way around from time to time; the tapping of the cup being vigorous enough to disturb the sand grains and allow them to rearrange themselves.

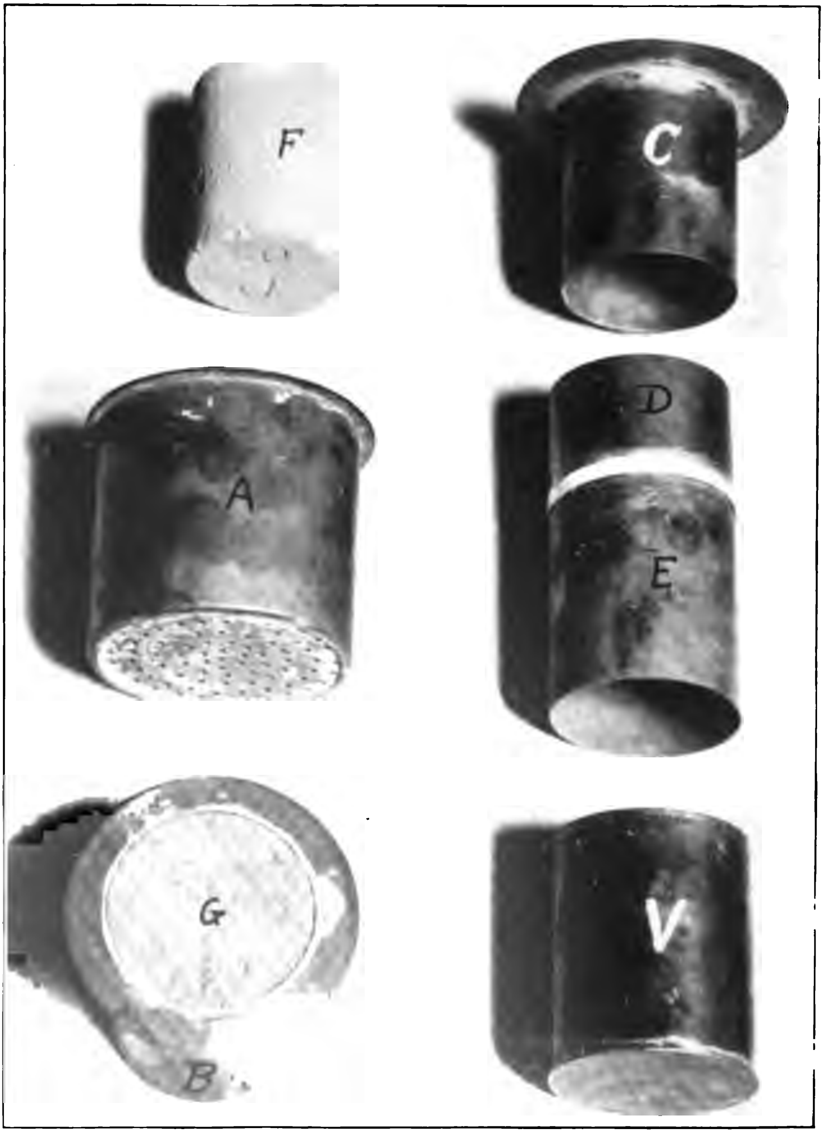

FIGURE 6. BRASS CYLINDERS USED FOR MOUNTING CORES OF MOLDING SAND FOR PERMEABILITY TESTS; AND CUP *V* USED IN POROSITY DETERMINATIONS

After the sand had settled as much as it would by jarring, the extra section was removed from the cup, the top of the cup was stricken off with a metal straight edge, and the cup and contents weighed. Subtracting the net weight of the sand in the cup from 615.6, the weight of the same volume of solid rock, and dividing the difference by 615.6 gives the pore space in the sand in percentage of volume.

Other methods of determining the pore space were tried, such as adding sand to a measured volume of water and noting the volume of water displaced by the sand, but the results were unsatisfactory because of entrained air.

More refined methods of determining the pore space did not seem warranted because the per cent of pore space in sand is not a dependable measure of the permeability. Even in loose clean sand the permeability can be judged only in a very general way from the porosity, and in damp loams where granulation takes place there is no necessary relation between the actual porosity and the observed permeability. Permeability on the other hand is of vital importance, and this was determined directly by testing the sand without reference to its porosity.

The porosity of a large number of dry sands was determined by the method above described; that of the damp sands and cores was computed from the known weight, volume, and other factors; and the results appear in the various tables throughout the report. The porosity determinations included in the tabulations show that the permeability commonly is independent of the porosity.

Testing the permeability of molding sands.—Permeability of sand is the facility the sand offers to the passage of a liquid or gas through it. Permeability in sand is usually measured by the time required to pass a given volume of air through a column of sand of known dimensions.

For testing permeability, apparatus was designed and built that would deliver 74 liters of air at a constant pressure of 50 inches of water. In some respects this apparatus was adapted from the aspirator used by King.[7] A standard column of sand 2 13/32 inches in diameter and 3 inches high was used in all permeability tests. The time required to pass the 74 liters of air through the columns of sand was measured by a stop watch, which could be read to a fraction of a second.

One hundred eighty samples of sand and loam were tested for permeability with this apparatus, and an average of six runs was made on each sample. The time of passage of the air ranged from 24 seconds to 4,646 seconds in the different samples. The pressure of the air remained practically constant, varying less than ½ of one per cent during the rapid runs, and being absolutely constant during the slower runs.

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[7] *Op. cit.*, p. 223.

The apparatus used to test the permeability of sands is shown in Figure 7. The apparatus consists of a series of chambers made of large threaded iron pipe in which the air was compressed by admitting water into the chambers. The apparatus is connected directly with the city water system, which has a pressure of 65 pounds, thus insuring an ample supply of water as rapidly as may be needed. The water is admitted into the apparatus through a 2-inch gate valve at *I*. It passes through chambers *EA* and *AB* and into *CD*, each of which is 6 inches in diameter, compressing the air as it advances. A weir 6 inches across is provided at *L*, over which the water passes into chamber *CD*. A stand pipe 4 inches in diameter is provided at *F*, open at the top, with an overflow for waste at *G*. The waste gate *G* is 50 inches above the weir *L*.

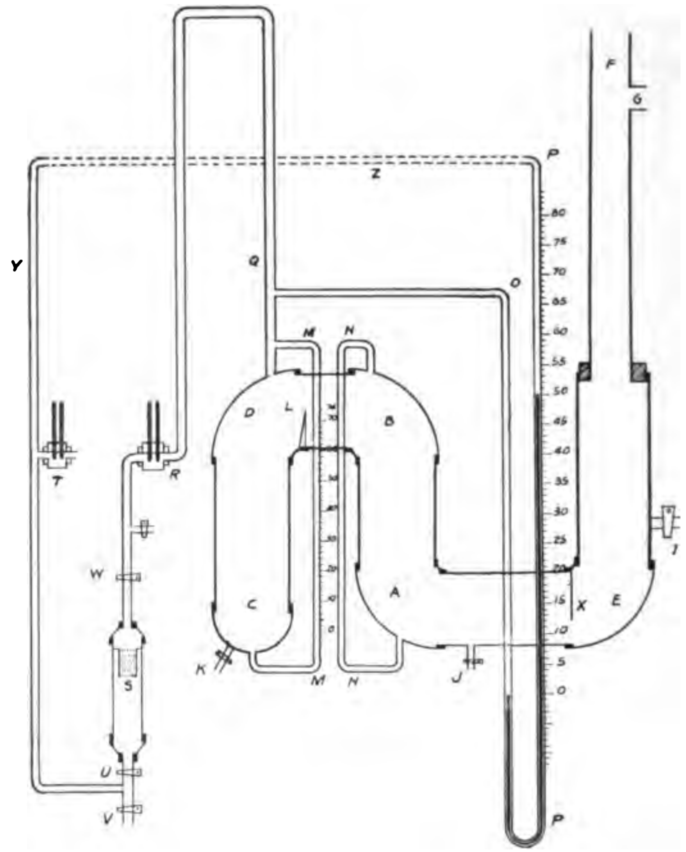

FIGURE 7. APPARATUS USED IN PERMEABILITY TESTS DELIVERING 74 LITERS OF AIR UNDER CONSTANT PRESSURE OF 50 INCHES OF WATER

which insures a uniform head of 50 inches of water, giving a pressure of about 4.5 pounds.

The compressed air is conducted through a 2-inch pipe *Q*, which extends 20 feet above the apparatus, returning to *R*, where wet and dry bulb thermometers are installed in the air line. From *R* the air is conducted downward through a common well cylinder in which the sand sample to be tested is mounted at *S*.

After passing through the sand *S* the air is carried upward and through a waste valve at *T* in which another set of wet and dry bulb thermometers is installed. A water manometer *OPP* is connected with the air line *Q* and provided with a scale, graduated to 1/10 of an inch. The manometer registers the pressure, 50 inches, direct, and variations in pressure can be read to 1/10 inch, or .2 of 1 per cent of the total pressure.

Chambers *AB* and *CD* are provided with glass water gauges *MM* and *NN*, which show the height of the water in these chambers at all times. The volume of chamber *CD* was determined by measuring water into it when the apparatus was installed. The glass gauge *MM* was provided with a scale, and the calibrations in half liters were marked on this scale as the water was measured into the chamber *CD*. The chamber *CD* holds 74 liters to the level of the weir *L*, which is the capacity of the apparatus. When in operation the amount of air that is passed through the sample is registered at all times by the position of the water level in gauge *MM*.

Waste valves are provided at *K* and *J* to empty the apparatus of water after a run is completed. A baffle at *X* serves to make the greater part of the air in chamber *AE* available for compression, and to prevent undue agitation in chamber *AE* when the city water under high pressure is admitted.

Control valves are provided at *U*, *V*, and *W*. The wet bulb thermometers at *T* and *R* have the bulbs wrapped with lamp wicking, and a small chamber filled with water is provided below the air line beneath the wet bulbs, in which the wicking is submerged, thus providing the wet bulbs with water to meet the needs of evaporation.

The upper end of the waste pipe *Y* is connected with the upper end of the manometer *P* to guard against, and register any back pressure that might result from friction or otherwise when air is passed rapidly.

The procedure in testing is as follows: The sand to be tested is mounted in the well cylinder at *S*; the valves *U* and *V* are closed; the valve *I* is opened, admitting the water into the apparatus rapidly so that it overflows in considerable volume at *G*. The rise of the water in chamber *AB* is registered in the glass gauge *NN*, and the rate the water rises here naturally declines as the pressure increases. The manometer

OPP records the pressure as it progresses. When the water in chamber *AB* reaches the level of the weir *L*, which is indicated by a calibration mark on the gauge *NN*, the manometer is read. The valve *U* is then opened allowing the compressed air to pass through the sample. When the water in chamber *CD* reaches the zero mark on gauge *MM* the stop watch is started and allowed to run until the water in chamber *CD*, as registered on the gauge *MM*, reaches the calibration 74, indicating that 74 liters of air have passed through the sand. The watch is stopped the instant the gauge *MM* registers 74, so that the time is recorded to a fraction of a second. The valve *I* is then closed, and the valves *J* and *K* opened to empty the apparatus.

The temperature of the room and the barometer is recorded at the beginning of each run, and the wet and dry bulb thermometers at *R* and at *T* are read three times or more during each run, viz., the beginning, at the middle, and at the end of the run.

The apparatus was readily tested against any possible leaks from defective mounting or improperly seated valves by allowing a little water to come over the weir into chamber *CD*, then closing the valve *U*, and allowing the water to run, wasting at the overflow *G*. If there were any air leaks the water would rise in the chamber *CD* and register on the gauge *MM*. Testing the apparatus consisted in allowing it to stand for a period equal to the time required to pass the 74 liters of air through the sample; that is, if it required 100 seconds to pass 74 liters of air through the sample, the apparatus was allowed to stand 100 seconds under full pressure. If the leaks were not appreciable in that time, they were neglected.

The pressure rarely varied more than .3 of an inch during a single run, which is .6 of 1 per cent. The variations in pressure were greatest with rapidly passing air; that is, when the time of passing the air was 50 seconds or less, the variation in pressure might be as high as .6 of 1 per cent, but when the time was 200 seconds or more, the variation in pressure was rarely more than .1 inch on the manometer, or .2 of 1 per cent. The average pressure for hundreds of tests was 50.45 inches.

The apparatus used for mounting the samples of sands is somewhat elaborate, due to the wide range of material tested. The main container consists of a common, brass lined, well cylinder 3½ inches in diameter and 12 inches long, the plunger and lower valve being removed, and the barrel of the cylinder with the upper and lower caps only retained. This is installed in the air line, as shown in Figure 7, between the valves *U* and *W*. A brass cup of heavy gauge metal (Fig. 6 *A*) was made to slip inside this cylinder barrel. It has a ¼-inch flange at the top, resting on the upper end of the cylinder barrel under the leather gasket, insuring an air-tight joint. The bottom of the cup is heavy stiff brass, perforated. All of the samples were mounted in this cup, the method being adapted to the nature of the sample.

When damp or green sand is tested the sample is rammed into a special cylinder (Fig. 6 *B* and *C*) of the same dimensions used in the porosity tests, viz., 2 13/32 inches in diameter by 3 inches long, open at the ends and having a flange ¾ of an inch wide at the upper end. The flange rests on top of the cup beneath the leather gasket, thus insuring an air-tight joint, and compelling all of the air to pass through the sand core. The lower end of the sand core in this cylinder is supported by building up the bottom of the brass cup with discs of brass wire screen cloth of 20-mesh.

When loose sand was tested, the same cylinder (Fig. 6 *C*) was used. To retain the sand a false bottom of screen cloth was slipped on over the cylinder. The loose sand was compacted in the cylinder by rapping the side of the cylinder to jar the contents. The cylinders of loose sand were mounted in the brass cup in the same manner as the damp sand.

Where dry cores of sand (Fig. 6 *F*) were to be tested, it was necessary to provide some envelope that would fit the side walls of the core tightly enough to prevent any air by-passing along the sides of the core between the core and the envelope. Two types of envelopes were used to accomplish this purpose, and the cores were mounted in the brass cup as follows:

1. The cores by one method are coated with melted paraffin, care being exercised to have the paraffin no hotter than needed to apply it. If paraffin is too hot and fluid, it permeates the core and diminishes its permeability. After coating with paraffin, the core is set in the center of the brass cup, and the space between the core and the sides of the cup, about one half inch, is filled with puddled clay in a semifluid condition. The bottom of this space is filled with cotton waste and a little sand, to prevent the fluid clay passing through. This type of mounting was found to be absolutely impermeable.

2. The second type of envelope used for the dry cores consists of a sleeve of very thin sheet rubber, such as dentists use, which they call "rubber dam." These sleeves are made with a diameter less than the diameter of the core, vulcanizing the seam. The sleeves are stretched and slipped over the cores. The cores with rubber envelopes are mounted in the brass cup in the manner above described, using puddled clay in the intervening space. Paraffin was tried instead of puddled clay, but with unsatisfactory results, since the paraffin on cooling would shrink and draw away from the walls of the cup.

It is well known that to devise an apparatus that will deliver a definite volume of air at a constant pressure is a most difficult problem. The most serious fault with the apparatus used by King was that the volume of air employed was small and the pressure low, and because of this the barometric pressure with its diurnal variation, the humidity of the air, and the temperature of the air became important variable factors that had to be taken into account and determined with each run made. By greatly increasing both the volume of air passed and the pressure, these variables became practically negligible.

In making the tests of the permeability of the molding sands a record was kept systematically of the barometric pressure, temperature, and humidity of the air to determine to what extent these variables were factors in the problem; but it was found that the corrections necessitated on this account were so slight that they could be ignored without appreciably affecting the results.

RELATION OF POROSITY, TEXTURE, AND STRUCTURE TO PERMEABILITY

In ordinary sand and loam such as are used in foundries the interstitial spaces between the sand grains, called the voids, communicate with one another, forming continuous tube-like passages which the air in passing through the sand follows. They are very small, hair-like, in size. The movement of air through sand has been demonstrated by laboratory experiment to be comparable, within certain limits, to the movement of air through capillary tubes, indicating that the interstitial passages through sand are capillary in size.

The size of the interstitial tubes in sand is a function of the size and arrangement of the individual grains. Slichter has shown that in a mass of perfect spheres arranged in the most compact form, shown in Figure 8, the area of the cross section of an interstitial tube through the mass is $.1613\ r^2$, in which r is the radius of the individual sphere.[8]

The rate that air will pass through capillary tubes of different diameters and the same length is in proportion to the square of the area of the cross section of the respective tubes. With two capillary tubes the areas of the cross sections of which are 2 and 4 square microns respectively the rate of the passage of air through them would be in the ratio of 4 to 16. From which it will be seen that the size of the interstitial tubes in sand is of vital importance as effecting the permeability.

Texture in sand is that property which is related to, and dependent on, the size of the individual grains. For example, a sand in which the grains were all of the 20-mesh size, or in which the 20-mesh sand predominated, would be said to have a coarse texture; whereas a sand in which all of the grains were of the 80- or 100-mesh size, or in which these sizes predominated, would be said to have a fine texture. Structure in sand has reference to the arrangement of the grains with respect to each other without regard to their size.

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[8] Slichter, C. S. Theoretical investigations of the movement of ground water: U.S. Geol. Survey Nineteenth Ann. Rept., part 2, p. 316, 1899.

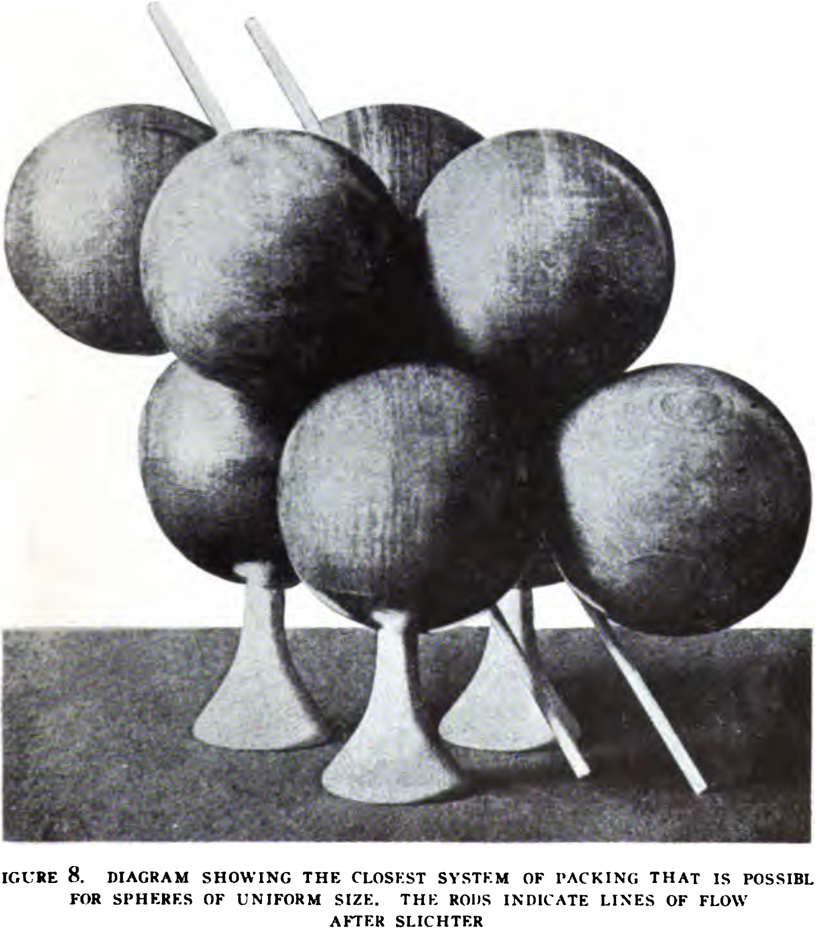

FIGURE 8. DIAGRAM SHOWING THE CLOSEST SYSTEM OF PACKING THAT IS POSSIBLE FOR SPHERES OF UNIFORM SIZE. THE RODS INDICATE LINES OF FLOW AFTER SLICHTER

The permeability of sand is dependent on each of these properties, the relative importance of which varies with the individual case. Reference to Figures 9, 10, and 11 may serve to make clear why this is true.

Figures 9A and 9B illustrate the effect of texture on permeability. The structure is the same in both 9A and 9B; that is, the spheres are systematically placed in the most open arrangement with each sphere touching six other contiguous spheres. The spheres in Figure 9B, however, are just one half the diameter of the spheres in Figure 9A, and accordingly there are four times as many interstitial tubes in the mass 9B, as there are in the mass 9A. The total interstitial space, or porosity, is the same in both 9A and 9B, viz., 47.6 per cent. Therefore the interstitial tubes in the mass 9A must be four times as large as the interstitial tubes in the mass 9B. The areas of the cross section of individual tubes in the masses 9A and 9B would be in the ratio of 4 to 1; but according to the law stated in the preceding page the rates at which air would pass

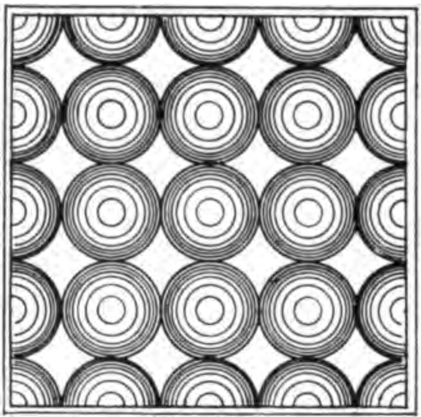

Fig. 9A

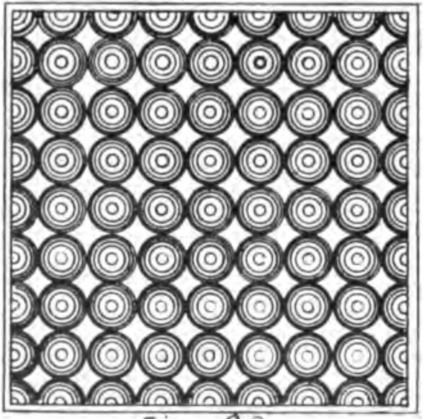

Fig. 9B

FIGURE 9A AND 9B. ILLUSTRATING STRUCTURE IN MASS OF SPHERES IN MOST OPEN ARRANGEMENT IN WHICH VOIDS EQUAL 47.6 PER CENT OF THE VOLUME OF THE MASS

After F. H. King

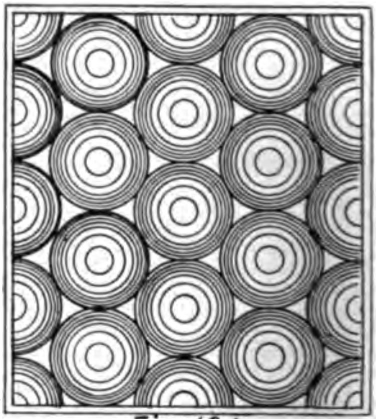

Fig. 10A

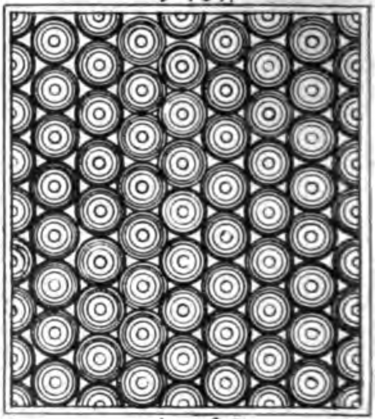

Fig. 10B

FIGURE 10A AND 10B. ILLUSTRATING STRUCTURE IN MASS OF SPHERES OF SAME SIZE AS FIGURE 9 IN MOST COMPACT ARRANGEMENT, IN WHICH THE VOIDS EQUAL 25.9 PER CENT OF THE VOLUME OF THE MASS

After F. H. King

through these individual tubes in masses 9A and 9B would be in the ratio of 16 to 1. Since there are four times as many tubes in 9B as in 9A the rate at which air would pass through the two masses 9A and 9B would be in the ratio of 4 to 1; that is, the mass 9A would be four times as permeable as the mass 9B, notwithstanding the porosity is the same and the structure is the same in the two masses. The only difference in the two masses is that 9B is of finer texture than the mass 9A.

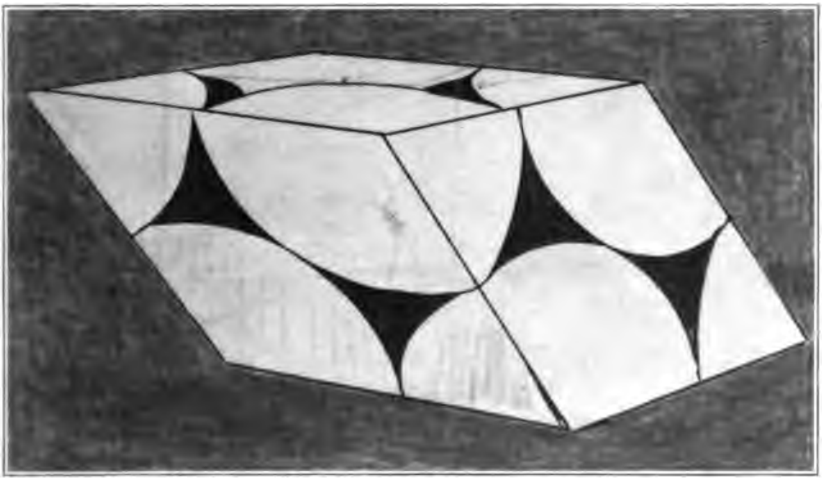

FIGURE 11. ILLUSTRATION OF RHOMBOHEDRON CUT FROM MASS OF SPHERES IN MOST COMPACT ARRANGEMENT, SHOWING ARRANGEMENT, RELATIVE SIZE, AND COMMUNICATION OF INTERSTITIAL SPACES
AFTER SLICHTER

The size of grain is the same in Figure 9A and in Figure 10A, but the arrangement of grains, or structures of the masses is different. The spheres shown in Figure 9A are placed in the most open arrangement possible, with each sphere touching six other spheres,[9] whereas the spheres shown in Figure 10A are in the most compact arrangement possible, with each sphere touching twelve other contiguous spheres. The porosity of the mass 9A is 47.6 per cent; that of 10A is 25.9 per cent. There are sixteen interstitial spaces in 9A and thirty-two in 10A, with an equal number of sand grains. The ratio of numbers of pores is therefore about 1 to 2.

If one pore in 9A had an area of 47.6 units, a single pore in 10A would have an area of about one half of 25.9 units, or 12.95 units, roughly one fourth the area of the pores in 9A. The permeability varying as the square of the area of a pore (here a tube) would be 16 times as great in each tube of 9A as for each tube of 10A. But there are about twice as many tubes in 10A, so that the permeability of a mass like 9A will be roughly 8 times as great as that of 10A. This great difference in permeability is independent of the size of sand grain used, so long as they are uniform spheres. The difference is wholly a matter of arrangement of grain or structure in the two masses.

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[9] Four spheres only are shown in the figure which is a cross section but two other spheres are not shown; one is at the front, another at the back of section. In figure 10A only six spheres are shown of twelve that touch each sphere.

Another illustration of the effect of structure on permeability is shown in Figure 12, where the intergranular spaces rather than the interstitial spaces determine the permeability of the mass.

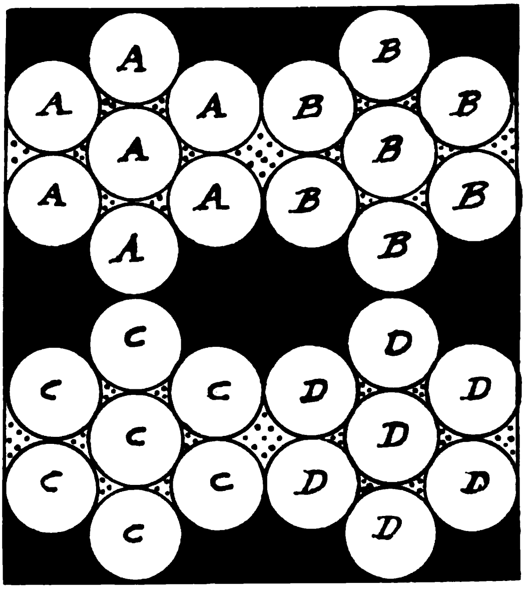

FIGURE 12. ILLUSTRATION OF GRANULATION IN WHICH SPHERICAL GRAINS ARE BOUND TOGETHER IN COMPACT GRAINS OR GRANULES ARRANGED IN OPEN STRUCTURE WITH LARGE INTERGRANULAR SPACES

AFTER LYON, FIPPEN, AND BUCKMAN

Each of four granules *A*, *B*, *C*, and *D*, is made up of spherical grains placed in the most compact arrangement, and the granules in turn are arranged in open structure so that each granule touches six other granules, leaving relatively large intergranular spaces. In a structure of this kind the spaces between granules or groups of spheres alone would amount to more than 40 per cent of the mass; in addition to which other spaces between spheres amounting to about 15 per cent of the entire mass, would give a total of about 55 per cent of voids. The smaller tubes between grains in the granules would be so small, however, compared with the intergranular tubes, that they would have little effect on the permeability. Owing to the large intergranular tubes the permeability of the mass would be very great.

The case illustrated in Figure 12 is hypothetical. In natural sands the grains are never perfect spheres, nor are they ever symmetrically arranged. On the other hand in molding sand that has been tempered with the proper amount of moisture, granulation does occur and the permeability of such tempered sand is usually greatly increased as a result of the granulation. In soils these clusters or compound grains have been termed the "effective grain" because they behave as unit masses and give to the soil a structure and a permeability the same as though the soil were made up of particles of this size. In soils or in molding sand, however, the compound grains or granules may be made up of hundreds or even thousands of individual particles instead of a few particles as illustrated in Figure 12.

As to the effect of granulation on permeability in molding sands a single illustration will suffice. In Table XVI, it will be observed that with sand 240, in the loose dry state in which the sample had been pestled to break up the compound grains into individual particles, it required 2.027 seconds to pass a given volume of air through a standard cylinder of the dry sand, whereas the same sand moistened, tempered to facilitate granulation, and then rammed into the same cylinder allowed the same volume of air to pass in about one tenth of the time, viz., 244 seconds. The greater permeability of the same sand in the damp molded condition was plainly the result of granulation.

EFFECTIVE SIZE OF GRAIN

In natural sands of unassorted sizes the interstitial spaces between the sand grains vary greatly in size and are more or less haphazard in arrangement, but it has been demonstrated mathematically, and confirmed by laboratory experiment, that with clean loose sand grains of mixed size there is a mean, or average grain, called the "effective size"; and that the permeability of such sand is the same as though the mass were made up entirely of grains of this effective size. It has been shown also that within certain limits the movement of air through sands made up of grains of mixed sizes is amenable to the laws governing the movement of air through masses made up of grains spherical in form and symmetrical in arrangement.

It has been shown by Slichter that in masses made up of spherical grains in most compact arrangement the area of the cross section of interstitial tubes is $.1613\ r^2$, in which r is the radius of the individual sphere. But because of the irregularity in outline of the cross section of such a tube, not all of this area is to be counted as effective in the passage of air. Making allowance for this factor, Slichter computes the effective area of cross section of interstitial tubes in granular masses such as above described to be .1475 r^2, in which r is the radius of the individual sphere in the mass.

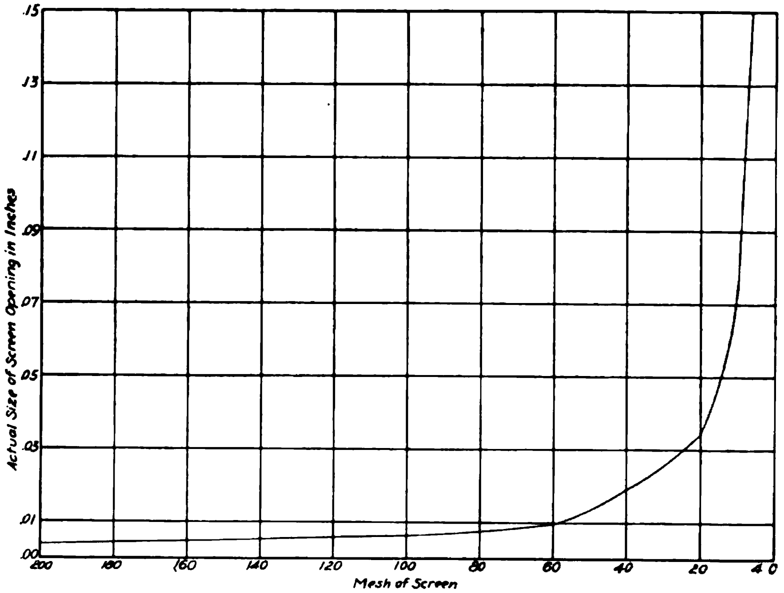

FIGURE 13. DIAGRAM SHOWING RELATIONS OF MESHES OF SCREENS AND ACTUAL SIZES OF OPENINGS

A determination of the size of the granules, or compound grains, was not attempted because numerous factors were involved, the relative values of which have not been determined. The laboratory work was devoted largely to special problems submitted by foundries, and a determination of the actual and comparative permeability as measured by the time required to pass a standard volume of air through particular samples of sand was all that was necessary.

METHOD OF COMPUTING PERCENTAGE PERMEABILITY

For comparing the permeability of sands, it is convenient to have some factor other than the time of passage of the air to express the relative permeability of different sands. Accordingly standard Ottawa sand was taken as a standard for comparison, and assumed to be 100 per cent permeable. The standard sand used in these experiments, sample 215, showed by screen analysis less than 1/10 of 1 per cent coarser than 20 mesh and less than 1 per cent finer than 30 mesh.

In the permeability apparatus sand 215 showed as a result of seven tests that it required 24 to 26 seconds to pass the standard volume of air, 74 liters, through this sand, giving an average of 25 seconds. Assuming this sand to be 100 per cent permeable and 25 seconds to be the time required to pass the standard volume of air through it, then the percentage permeability of the other sands was calculated by the formula $\frac{25}{Y} = Z$, in which Y is the time required to pass the standard volume of air, 74 liters, through the sand whose permeability is sought, and Z is the percentage permeability. For example, with sample 9, it required 94 seconds to pass the standard volume of air through the sand, accordingly $\frac{25}{94} = 26.6$ per cent, and 26.6 is taken as the per cent permeability of sand 9. Sample 240A required 2,027 seconds to pass the standard volume of air, and $\frac{25}{2027} = 1.2$ per cent is the permeability of this sand.

In making the permeability tests the same practice was followed as in making tests for bond, i.e., such samples as were molded were made in triplicate, and the average taken of three tests. A core box was used in most cases, permitting the making of three cores at a time. Where possible each core was run successively for green, for dry, and for baked test; that is, the core was put in the permeability apparatus directly from the mold and tested for permeability while damp or green. It was then allowed to stand in the laboratory 24 to 48 hours to dry, after which it was run again as an air-dried core. The same core was then placed in the bake oven at 400° C. for 4 to 8 hours, after which it was allowed to cool and was tested again for permeability as a baked core.

It frequently happened that the cores of sand molded directly in the solid cylinders became loose in the cylinders after drying, as a result of shrinkage from loss of moisture. In such cases the cores were removed from the cylinders and provided with a special mounting, using a seal of melted paraffin or puddly clay to insure against leakage of air around the sides of the core, and compelling all of the air to pass through the core itself.

The apparatus was so arranged that the pressure could be brought to the standard amount, namely, 50 inches water, and held there for any period desired. By observing the manometer and the water gauge, any leaks in the mounting were at once detected and corrected before making the run.

SHAPE AND ARRANGEMENT OF INTERSTITIAL TUBES IN SAND

The shape and arrangement of the interstitial spaces or voids in a mass of sand, and the manner in which these voids communicate to form interstitial passages or paths through the mass is illustrated in Figures 8 and 11. The grains of the mass in these illustrations are perfect spheres most compactly arranged, in which the pore space is about 26 per cent. It will be observed that the interstitial tubes through the mass, indicated by the rods, in Figure 8 are inclined at an angle of 30° from the vertical. They form passages following rectilinear paths through the mass, and as Slichter has shown the length of these passages or interstitial tubes is 1.065 times as great as a direct line through the mass normal to the base or top of a sand column. Accordingly in the cores of sand used in the permeability experiment, which were 3 inches long, the actual length of the interstitial tubes through these cores would be about 3.195 inches.

In the flow of air through capillary tubes the length of the tube as well as its diameter is a function of the rate of flow. The formula for computing the flow of air through capillary tubes was worked out experimentally by Poiseuille in 1842, and is known as Poiseuille's Law. The proper ratio of the length of a capillary tube to its diameter in order that Poiseuille's Law shall hold is about 6,000 to 1. This should be taken into consideration if the results given in Table XVI are to be checked against Poiseuille's Law.

Cores used in permeability tests of sands, loams, and clays.—The purpose of the permeability test was to obtain actual figures on the comparative permeability of different kinds of sand under conditions comparable to those in the foundries rather than as a study in permeability *per se*. The actual dimensions of the cores as finally chosen were determined by several considerations as follows:

1. The depth of the core, or length of the sand column, should be comparable to the thickness of the walls of molds in ordinary foundry work. Three inches was thought to be a fair average thickness for such molds, and accordingly a core 3 inches deep was chosen.

2. The structure in a sand mass adjacent to, or in contact with, the walls of the container is necessarily somewhat different from what it is in the center of the mass. This is especially true in damp sands that are rammed into the container, because of the drag of the sand on the side walls. Accordingly the larger the diameter of the container the less serious this factor becomes.

3. The air passages through a sand tend to follow rectangular paths and some of these paths meet the side walls and have their courses deflected. The larger the diameter of the container, the less the percentage of the air

passage that will be interrupted in this manner, and the more nearly the test cylinder approaches normal conditions.

4. A sand column the length and diameter of which are the same will probably most nearly approach foundry conditions, and accordingly a core was sought as near 3 inches in diameter as practicable.

5. It is desirable to use brass cylinders of heavy gauge so that the walls are not deformed, or the cross section of the sand column distorted by ramming sand into the cylinders, or by air pressure. Furthermore the plan of the work contemplated a large number of these cylinders for use in the foundries, and it was essential that they be as near the same dimensions as possible. It was found that common rolled brass tubing met the requirements, but such tubing 3 inches in diameter was not readily available and tubing 2 13/32 inches in diameter was chosen as the nearest approach to the dimensions desired. The containers were made by cutting sections 3 inches long from such tubing.

FUSION TESTS

The fusion tests of sands consisted in burning two or more briquets of the various sands in an electric furnace, the temperature of which was controlled, and noting the effect of temperatures ranging from 400 to 1,000 degrees C. The furnace was provided with a window or peephole, so that the behavior of the samples could be observed as the temperature was increased. Seger cones were used in the furnace along with the samples, following the usual practice in ceramic work, as a check on the furnace temperature. The laboratory work in fusion tests was not sufficiently complete to be made the basis of generalizations, but was suggestive in that some of the sands that had ample bond, and gave satisfactory results in the foundry, disintegrated into loose sand in the furnace at temperatures of 600 to 1,000 degrees C, whereas other sands burned into fairly hard brick at the same temperatures. In general the temperatures reached were not high enough to cause even incipient fusion, although in a few cases the stage of vitrification was reached.

MOISTURE CONTENT OF MOLDING SANDS

Certain tests for moisture content of molding sand were undertaken with the following objects in view: (a) to determine the moisture content in sands and loams in actual use in the foundries; (b) to determine whether or not better results in tensile strength or permeability might be obtained by increasing or decreasing the amount of moisture from that used in the foundries; (c) to determine the variation in the moisture in the molding sands in the same foundry from day to day.

The results obtained served to show that there was a considerable range in the moisture content in the same foundry from day to day in the same kind of molding, the variation amounting to 30 per cent in some instances. There was also a variation in different foundries using the same grade of sand, and doing the same class of founding.

There was a variation in the moisture content in the same foundry as between different molders using the same sand. The results are recorded in the tables on tensile strength and permeability and are discussed in that connection.

The method of taking samples for moisture determinations was to use two quart glass fruit jars with the ordinary rubber gasket to insure against loss of moisture. The samples were taken from the molders' tables or from the sand heaps in actual use.

The method of determining the moisture content consisted in drying 100-gram samples of the sand taken in the foundry in the sand bath at 100 degrees C. for 24 hours or longer until they ceased to lose weight. and counting the loss of weight as moisture.

MECHANICAL AND MINERAL ANALYSES OF CORE SANDS

Results of the mechanical analysis of core sands are recorded in Table IX. Forty samples were analysed, following both the dry method, A, and the wet method, B, above described. The analyses by the dry method, A, are not recorded except in cases where the wet method, B, was not completed. The 19 analyses recorded in Table IX were selected as being typical of the total number made.

Eight of the analyses given in Table IX are of samples obtained in the foundries of sands in actual use in core work. The remaining samples, the analyses of which appear in Table X, were collected in the field from various parts of the state as representing material similar in character to that in use for core work.

One sample, 252A, used for core work in exceptionally heavy gray iron work, was obtained by the foundry from local glacial drift, having been washed at the pit to remove the greater part of the clay, and screened to remove the gravel coarser than 1/4 inch in diameter. The other samples of core sand in use in the foundries were obtained from the St. Peter formation in St. Paul and Minneapolis.

The analyses, Table IX, show that sand suitable for core work may be obtained from the St. Peter formation carrying less than one half of 1 per cent of clay, but most of the sands in actual use carry 1 to 2 per cent of clay.

The texture of the core sands in actual use in the foundries is indicated in a general way by the "mesh" recorded in Table IX. The range for samples of sand used, except 252, is from 52 to 72. Sample 5, with a comparative mesh of 52, is the common type. The method of computing the comparative mesh, and the purpose in using the term to express texture is explained above, under Laboratory Methods. Sample 90, showing a mesh of 38, was the coarsest sand found in the St. Peter formation.

For ordinary core work the St. Peter sand is very satisfactory, and there is an unlimited supply available. The strictly clean sand is not necessarily the best. Samples 28 and 31 were used in the same foundry, and both came from the St. Peter formation. Number 28 was a clean, white, quartz sand, whereas 31 was stained yellow by oxide of iron. The yellow sand was the more satisfactory, as it developed greater tensile strength and gave smoother surfaces to the castings.

Where coarser sand was desired for heavy core work, this was obtained by mixing sand from the Jordan formation, described under steel sand, with the St. Peter sand. Coarser sand is obtainable from the St. Peter formation, but it is usually present as comparatively thin horizons, of 2 to 6 feet, interbedded with sand of the finer type. It is not feasible in most instances to develop it because of the overburden of fine material, and because of the excessive expense of mining it by tunneling. It is cheaper ordinarily to purchase the coarser sand from the Jordan formation and raise the average mesh by doctoring the St. Peter sand.

Owing to the rather wide variation in the requirements of core sand for the different classes of founding, no single grade of sand meets all of the needs. For core work in brass, and light work in grey iron, a sand of about 57 average mesh is preferred, and for heavy work in grey iron and steel an average mesh of about 35. In general, while a clay content is not essential, 1 per cent of clay or even more, is no detriment. The entire absence of silts is preferred, but the presence of 1 to 5 per cent of silt does no apparent harm.

Samples 90, 145, and 278 were collected from the St. Peter formation at Cannon Falls, Rochester, and Northfield respectively and illustrate the uniformity of the sand in this formation throughout the state.

Sample 72 was collected at Daytons Bluff, St. Paul, from the St. Peter formation, and illustrates the type of very fine sand that occurs in the St. Peter formation at certain horizons.

Samples 152 and 279 were collected from pockets and lenses of sand that occur more or less commonly in the dolomitic limestone between the Jordan and the St. Peter formations.

Sample 104 was collected from the Cretaceous formation in Goodhue County. It is of no commercial importance.

The St. Peter and Cretaceous sands are largely quartz. Number 252 is a glacial sand and has about 22 per cent of minerals other than quartz. As it is being used successfully, it would indicate that mineral composition is of little importance. From the standpoint of refractoriness, those highest in quartz should be best, but actual practice shows that others can be used with a fair degree of success. In the northern part of Minnesota, glacial sands are used considerably for core work. One from Biwabik is used in the Virginia Foundry, and one from Brainerd is used by the Brainerd Foundry. Lake Superior sand is used for core work at Duluth to some extent.

TABLE IX. MECHANICAL ANALYSES OF CORE SANDS

Mesh of Screen	1B	5B	21B	28B	31B	64B	65A	67A
4— 10	....	....	....	....	....	....	....	....
10— 20	....	1.40	....	....	....	....	....	Trace
20— 40	.86	1.48	1.04	1.22	1.02	48.74	9.87	40.27
40— 60	16.24	56.66	41.38	54.68	40.58	39.56	58.76	40.45
60— 80	34.86	22.86	17.32	22.10	18.94	3.68	7.92	4.60
80—100	21.92	11.62	13.96	12.32	14.24	1.92	7.61	3.02
100—200	22.56	5.26	23.00	8.42	21.66	3.76	12.92	7.37
200-silt	1.04	.07	1.26	.24	1.36	.96	.26	2.42
15-minute silt	.10	Trace	Trace	.00	Trace	Trace	....	....
30-minute silt	.20	Trace	Trace	.00	1.00	.16	....	....
Clay	2.16	.05	1.44	.28	.46	.52	....	....
Total	99.94	99.40	99.40	99.26	99.26	99.30	97.34	98.13
Comparative mesh	72	52	59	55	59	39	51	41

1. Core sand, University of Minnesota, foundry, from St. Peter formation.

5. Core sand, Eagle Foundry, Minneapolis, used in grey iron work, from St. Peter formation.

21. Core sand, American Hoist & Derrick Foundry, St. Paul, used in grey iron work, from St. Peter formation.

28. Core sand, Northern Malleable Iron Works, St. Paul, from St. Peter formation.

31. Core sand, Northern Malleable Iron Works, St. Paul, from St. Peter formation.

64. St. Peter formation, Forty-second and Randolph Streets N.E., Minneapolis, four feet below top of formation.

65. St. Peter formation, same locality as No. 64, twenty feet below top of formation.

67. St. Peter formation, Washington Avenue N. and Thirty-ninth Street, Minneapolis.

TABLE IX—*Continued*

Mesh of Screen	72B	90B	104B	145B	152A	152B	252A	262A
4— 10	....	....	....	....	....	Sand	2.28	....
10— 20	....	....	....	....	....	not	14.76	....
20— 40	.16	57.00	3.12	48.92	20.36	screened	55.64	2.26
40— 60	.80	29.20	33.90	28.76	21.68	total	13.54	45.16
60— 80	.90	1.84	27.36	6.28	33.20		13.18	11.96
80—100	3.00	1.10	12.50	3.04	10.68	87.00	2.46	10.02
100—200	32.98	.94	12.02	5.40	6.65	....	1.16	28.84
200-silt	59.52	.52	3.20	5.14	6.54	....	.70	1.06
15-minute silt	Trace	.00	.60	Trace	....	1.00	....	....
30-minute silt	Trace	2.48	.36	1.84	....	5.00	....	....
Clay	1.76	2.26	5.62	3.40	....	5.74	....	....
Total	99.12	95.34	98.68	102.78	99.11	98.74	103.72	99.30
Comparative mesh	230	38	60	41	52	....	27	57

72. St. Peter formation, Daytons Bluff, St. Paul.
90. St. Peter formation, Cannon Falls, Minn.
104. Cretaceous formation, four miles southwest of Goodhue, Goodhue County, Minn.
145. St. Peter formation, Klines' quarry, Rochester, Minn.
152. Oneota formation, sand bed in limestone, Orinoco, Olmstead County, Minn.
252. Core sand, Eagle Foundry, Minneapolis, used in heavy core work from the glacial drift, washed.
262. Core sand, Soo Line Railroad Shops, used in brass founding, from St. Peter formation.

Mesh of Screen	278B	279B	282B	299A	299B
4— 10	....	....	....	....	....
10— 20	....	....	....	....	Sand
20— 40	3.00	14.82	.42	.90	not
40— 60	22.00	57.62	29.20	48.94	screened
60— 80	26.52	16.30	16.54	19.44	total
80—100	18.00	5.00	13.84	14.04	
100—200	21.28	4.54	31.58	15.50	98.54
200-silt	5.04	2.04	2.30	1.10	....
15-minute silt	1.06	.16	.20	....	.00
30-minute silt	1.22	.64	.20	....	.18
Clay	1.40	1.82	2.26	....	1.58
Total	99.52	102.94	96.54	99.92	100.30
Comparative mesh	68	49	68	57	....

278. St. Peter formation, Northfield, Minn.
279. Shakopee formation, Cannon Falls, Minn., sand in limestone.
282. St. Peter formation, Twin City Brick Co., St. Paul.
299. Core sand, Flour City Ornamental Iron Works, foundry, Minneapolis, from St. Peter formation, used in brass and bronze ornamental founding.

MINERAL ANALYSES OF CORE SAND

NUMBER	64	104	278	252
Part examined (over 200 mesh)	97.60%	92.4%	90.8%	100%
Quartz	99.2	98.97	99.3	76.16
Tourmaline	.02	.01	.07	.01
Limonite	.01	.18	....	.03
Kaolin	....	....	.26	....
Dolomite	....	....	....	9.41
Feldspar	....	....	....	7.11
Igneous rock	....	....	....	3.28
Hornblende	....	....	....	1.41
Chlorite	....	....	....	1.27
Augite	....	....	....	.11
Magnetite	....	....	....	.01
Biotite	....	....	....	.01

MECHANICAL AND MINERAL ANALYSES OF STEEL SANDS

The results of analyses of the coarser quartz sands, known as steel, fire, and silica sand, are recorded in Table X. The chief difference between these steel sands and the core sands is in the size of the grains, that is the steel sands are coarser than the core sands as generally understood; but there are exceptions to this rule, for in very heavy work core sands are used quite as coarse as the so-called steel sands. Fire or silica sands are quartz sands of medium to coarse grain that are very refractory; that is, their ability to stand heat is equally as important as their texture. They may contain 2 per cent or more of clay, as does sand 9, but if so this clay also must be refractory.

Most of the silica sands, or steel sands used in the Minnesota foundries are obtained from the Jordan formation, and would probably show on chemical analysis 92 to 95 per cent silica. The St. Peter formation carries some coarse sand also, as shown above in Table IX, which is essentially the same as the Jordan sand; in fact the sized sands from the two formations can not be distinguished from one another. The quartz grains, particularly the larger ones, are exceptionally well rounded.

Samples 166, 167, 168, 170, 173, and 175, were collected from the Jordan formation in the valley of the Minnesota River between Mankato and Merriam Junction, while samples 8 and 19 were collected from the foundries, and came originally from this same region. The similarity in the analyses is apparent. There is a noticeable difference in the texture of the Jordan sands, the comparative mesh ranging from 28 to 42.

The wet analysis to determine the clay content was not made on all of the steel sands, but analyses 8 and 19, which are wet analyses, are representative.

Sample 136 was collected from the Jordan formation 10 miles north of the Iowa line, at Preston, Fillmore County, about 100 miles southeast of the area in the Minnesota River Valley. It is of no commercial value, except locally, but is of interest as showing the nature of the Jordan sand in this part of the state. This sample was not particularly coarse, but was practically free of silt and clay.

Sample 151 was collected from the Jordan formation 35 miles north of the location just mentioned, at Orinoco, Olmstead County. It differs from 136 in being coarser and in carrying 2 per cent of clay and 3 per cent of silts. Samples 136 and 151 resemble the St. Peter sands.

Sample 160 was collected from the Jordan fomation in the valley of Zumbro River, 2 miles below Mazeppa, Wabasha County, 12 miles north of Orinoco. In coarseness and in the content of clay and silt it resembles the Jordan sands, 75 miles to the westward in Scott and Le Sueur counties, in the Minnesota River Valley.

Sample 9, from Massilon, Ohio, differed from the local sands chiefly in having a slight matrix of semi-refractory clay that formed a very uniform coating over the sand grains, which was sufficient to mold the sand.

Samples 185 and 186 were collected at Sandstone, Pine County, 80 miles north of St. Paul, from the Kettle River formation. The Kettle River sandstone is extensively quarried at this point for building stone and the rubble is crushed for concrete aggregate. The samples represent the sand screenings from the crushers, which has been used in foundries as steel sand with satisfactory results. This sand is rather finer than the Jordan sand, and carries more clay and silt.

Sample 188 was collected from the Sioux quartzite, Nicollet County, in the quarries near Courtland below New Ulm. The quartzite here along the quarry joints has disintegrated under the influence of organic acids and has reverted to sand. It is of no commercial importance, but is of interest as showing the character of the original sand from which the Sioux quartzite was formed.

Sample 200, Table XIV, while not listed as steel sand, might be used to advantage for that purpose. It consists of screenings from the crushers at Jasper, Rock County, Minnesota, where the Sioux quartzite is crushed for concrete aggregate. It is practically pure quartz, very refractory, nearly free from clay and silt, and extremely angular.

Steel sand is imported from Ottawa, Illinois, for use in the foundries of Minneapolis and St. Paul, and while no analysis of this sand appears in Table X, this Illinois sand was tested and found to be identical in physical composition with several samples of the Jordan sand of Minnesota.

In this connection attention should be called to a confusion of terms. Some founders understand the term Ottawa sand to mean sand from

Ottawa, Illinois, while others understand it to mean sand from Ottawa, Minnesota. That the two towns happen to have the same name is a coincidence only. The sands are essentially the same. The Ottawa, Illinois, sand, however, happens to come from the St. Peter formation, whereas the Ottawa, Minnesota, sand comes from the Jordan formation some 200 feet below the St. Peter formation.

The requirements for steel sand are somewhat varied and for this reason no one grade meets all needs. For some purposes a content of refractory clay sufficient to mold the sand is desired and if this can be obtained in the natural state it is preferred. The Kettle River sand comes near meeting these requirements; the sand from the Jordan formation rarely does.

Since it is desired that steel sands show a silica content of 97 per cent or over,[10] the analyses indicate that the Jordan, Kettle River, and Sioux are satisfactory from a mineral standpoint for such use.

The comparative mesh of steel sand is about 42. The absence of silts in steel sand is preferred, but 1 to 3 per cent of silt is not a serious detriment.

TABLE X. STEEL AND FIRE SANDS

MESH OF SCREEN	8B	9B	19B	136A	151A	151B	159B	160B
4— 10	......	......	......	......	......	......	......	......
10— 20	3.44	.74	4.02	......	.36	Sand	3.08	1.18
20— 40	54.80	22.80	44.47	17.40	0.00	not	68.40	48.58
40— 60	29.54	26.06	27.08	28.88	20.02	screened	23.52	35.68
60— 80	4.68	25.08	5.56	31.96	36.40	total	2.52	9.04
80—100	2.30	10.00	3.96	15.52	13.72		.80	2.94
100—200	2.61	7.44	9.25	5.42	16.88	95.00	.42	.98
200-silt	.30	3.50	3.81	.28	12.44	......	.02	.00
15-minute silt	Trace	.12	.63	......	......	1.00	.00	Trace
30-minute silt	Trace	1.40	.10	......	......	2.00	.00	.24
Clay	.25	2.00	.98	......	......	2.00	.46	.92
Total	97.92	99.14	99.86	99.46	99.82	100.00	99.22	99.56
Comparative mesh	35	50	40	51	71	......	32	38

8. Steel sand, Gas Traction Foundry, Minneapolis, from Jordan formation, Ottawa, Minn.

9. Steel sand, Gas Traction Foundry, Minneapolis, from Massilon, Ohio.

19. Silica sand, American Hoist & Derrick Foundry, St. Paul, from Ottawa, Minn., Jordan formation.

136. Quartz sand, Jordan formation, at Preston, Fillmore County, Minn., 10 miles north of Iowa line.

151. Quartz sand, Jordan formation, at Orinoco, Olmstead County, Minn.

159. Quartz sand, Jordan formation, from Ottawa Sand Co., Ottawa, Minn.

160. Quartz sand, Jordan formation, at Mazeppa, Goodhue County.

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[10] Ries, H., and Rosen, J. A., Report on foundry sands: Ann. Rept. of Geol. Survey of Mich., p. 42, 1907.

MESH OF SCREEN	166A	167A	168A	170A	173A	175A	185B	186B
4— 10	......	.08	......	......	......	......	......	......
10— 20	.28	.00	2.24	1.76	5.34	3.64	......	......
20— 40	29.14	70.46	73.82	45.95	82.66	58.62	1.24	15.38
40— 60	62.20	26.00	22.18	35.36	10.48	30.80	39.56	21.08
60— 80	3.12	1.72	.56	7.08	.76	3.96	38.04	27.94
80—100	1.52	.58	.02	3.22	.16	1.44	8.84	15.44
100—200	1.66	.32	.20	3.98	.02	.48	5.84	9.60
200-silt	.12	.14	.16	.38	......	.04	1.20	6.30
15-minute silt	......	......	......	......	......	......	1.90	.54
30-minute silt	......	......	......	......	......	......	2.10	1.98
Clay	......	......	......	......	......	......	1.06	1.12
Total	98.04	99.30	99.18	97.73	99.42	98.98	99.78	99.38
Comparative mesh	42	33	31	39	28	34	58	55

166. Quartz sand, Jordan formation, at Kasota, Le Sueur County, Holverson's pit.
167. Quartz sand, Jordan formation, at Kasota, at River Bridge.
168. Quartz sand, Jordan formation, 1½ miles west of Merriam Junction, Scott County.
170. Quartz sand, Jordan formation, at Ottawa, Le Sueur County, Hayes' pit.
173. Quartz sand, Jordan formation, at Ottawa, Le Sueur County, Rayners' pit.
175. Quartz sand, Jordan formation, at St. Peter, Nicollet County
185. Quartz sand, Kettle River formation, at Sandstone, Pine County.
186. Quartz sand, Kettle River formation, same locality as 185.

MESH OF SCREEN	188B	220B
4— 10	......	......
10— 20	1.38	......
20— 40	39.08	46.62
40— 60	22.22	24.62
60— 80	19.76	14.24
80—100	7.48	7.30
100—200	5.26	5.92
200-silt	1.92	.74
15-minute silt	.34	.00
30-minute silt	1.88	.00
Clay	.32	.50
Total	99.64	99.94
Comparative mesh	44	42

188. Quartz sand, from Sioux quartzite, Nicollet County, near New Ulm.
220. Quartz sand, Jordan formation, at Ottawa, Minn., Potters' pit.

MINERAL ANALYSES OF STEEL SANDS

NUMBER	8	136	185	188
Part examined (over 200 mesh)	97.37%	99.1%	93.5%	95.1%
Quartz	99.00	99.2	99.17	98.57
Limonite	.28	.03	.01	.81
Biotite	.01	....	....	....
Tourmaline	.01	.01	....	....
Kaolin	....	....	.10	....
Magnetite	....	....	.01	....
Chlorite	....	....	.01	....
Feldspar	....	....	.01	.01
Chromite	....	....	.01	....
Hornblende	....	....	.01	.01

MECHANICAL AND MINERAL ANALYSES OF BRASS SANDS

The laboratory results of the mechanical analyses of brass sands are recorded in Table XI. About 75 samples of this type of material were examined, and 50 samples were subjected to analysis by both the dry method "A" and the wet method "B." The 34 analyses listed in Table XI are typical. The dry method analyses are omitted, except No. 70.

It will be observed from Table XI that the clay content of these sands ranges from 2.64 to 19.12 per cent. The 15-minute and 30-minute silts combined range from 4.00 to 36.47 per cent, and the comparative mesh ranges from 99 to over 250. The mesh is not stated for these sands but was calculated and nearly all ran above 150.

Of the 34 samples listed in Table XI, 18 were collected in the foundries and represents the type of material in actual use in molding in brass, bronze, aluminum, and the alloys of these metals. The remaining 16 samples were collected in the field in various parts of the state.

Four of the samples, i.e., 12, 213, 217, and 260, are floor sands; that is, sands that have been used one or more times, and consist of mixtures of raw brass sand and other materials, such as St. Peter sand and loam. The average mesh of these floor sands, which may be taken as representing the texture and constitution preferred in this class of work, ranges from 132 to 195, the clay content ranges from 3.46 to 5.80 per cent, and the silt content ranges from 4.94 to 11.28 per cent.

Four of the samples, i.e., 18, 210, 221, and 261, are so-called Albany sand, supposedly from Albany, New York. But the term Albany sand has come to be used as a trade name, and sands are sold under that name that do not come from Albany, New York. It is not known with certainty that any of the samples listed actually came from Albany. The founders only knew that the prices paid, including freight, were enough to have warranted the sands coming from that point.

NUMBER 75 Peter's pit, Fort Snelling. Furnishes brass sand

Part examined (over 200-mesh)	74%
Quartz	95.82
Hornblende	1.12
Feldspar	1.08
Biotite	.85
Muscovite	.15
Augite	.12
Magnetite	.10
Iron oxide	.05

Comparing the so-called Albany sands, Table XI, it will be seen that the clay content ranged as follows, 7, 3.74, 4.30, and 10.56 per cent. The silt content in these Albany sands ranged from 5.64 to 11.76 per cent.

The two brass sands from Missouri, samples 10 and 29, show the same wide variation in both clay and silt content; that is the clay content is 11.68 and 3.98 per cent respectively in the two sands, while the proportion of silt is in reverse order, viz., 7.66 and 21.6 per cent respectively.

The other brass sands exhibit the same wide range both in clay and silt content and in average mesh, from which it is apparent that the analyses afford no basis for a standard.

Sand 260, which was used for extremely heavy casting in brass, carried 3.96 per cent of clay and 4.94 per cent of silts, and may be close to the ideal brass sand. It is a mixture of so-called brass sand and other materials; it probably carries a considerable percentage of St. Peter sand.

Samples 16, 46, 48, and 51 represent material commonly present in the glacial drift in the vicinity of Minneapolis and St. Paul, occurring as irregular pockets and lenses. In view of the irregularity of the deposits and their lack of uniformity in quality, they are of little importance. Samples 75, 76, 77, 82, and 84 were collected in the Peters pit at Fort Snelling, which was the only pit furnishing brass sand to foundries at that time. These samples were collected in different parts of the pit and at different horizons from the surface to the floor of the pit, which was about 7 feet deep. The series shows the variation that may occur in the character of the material in this pit within a distance of a few rods. By selection of horizons in certain parts of this pit a very good quality of brass sand could be obtained, but uniformity in the grade is hardly to be expected. The analyses show that the clay content of the sands in this pit range from 2.87 to 13.64 per cent, and that the silts range from 4.08 to 31.23 per cent.

Samples 111, 124, 208, and 239 represent loess, vast quantities of which occur in the southeastern part of the state from Red Wing southward. The distribution is shown in a very general way in Figure 2. Thirty samples of loess were collected in various parts of the area and subjected to mechanical analysis. The four samples above mentioned, which appear in Table XI, are fairly representative of the group. The material is remarkably uniform in physical construction and is essentially the same as brass sand. In fact two tons of samples 208 were shipped to St. Paul and distributed among four different foundries and used as molding sand in brass with entirely satisfactory results.

Samples 295 and 296 were shipped in from Milwaukee, 295 being known under the trademark of "A.A.A." and 296 under the trade mark "A."

Because of the low temperature required for the melting of brass and its alloys, mineral composition would be expected to be less important than in other sands for foundry use. An attempt was made to make a mineral analysis of loess to contrast with that made on the

St. Peter, but the sand was too fine to give satisfactory results. The chemical analysis shows about what minerals are to be expected. See page 29. They undoubtedly include considerable feldspar, kaolin, and iron oxides.

XI. MECHANICAL ANALYSES OF BRASS SAND

MESH OF SCREEN	10B	11B	12B	16B	18B	29B	30B	32B
4— 10	....	....	....	....	.20	....	....	....
10— 20	....	.04	....	.32	.30	....	....	.28
20— 40	....	.16	.90	.44	.60	.12	.12	1.36
40— 60	....	.25	1.40	2.08	.54	.00	.74	.92
60— 80	.01	.50	4.06	.74	2.32	.34	1.54	1.52
80—100	.02	1.42	4.84	.50	3.38	.12	11.32	.96
100—200	.04	18.31	22.98	2.10	22.82	.52	24.50	2.52
200-silt	80.10	64.74	53.06	66.22	53.48	72.20	49.10	60.58
15-minute silt	1.94	.57	2.66	10.48	1.90	11.82	2.44	6.86
30-minute silt	5.72	3.45	4.32	14.68	7.00	9.78	4.86	13.44
Clay	11.68	10.36	3.46	6.30	7.00	3.98	5.16	9.66
Total	99.51	99.80	97.68	103.86	99.54	98.88	99.78	98.10

10. Brass sand, Gas Traction Foundry, Minneapolis, from St. Louis, Mo.
11. Brass sand, Union Brass Works, St. Paul, from Monmouth, Ill.
12. Floor sand, brass, Union Brass Works, St. Paul.
16. Lens of sand in glacial drift, Lawson and Mackubin Streets, St. Paul.
18. Brass sand, American Hoist & Derrick Co., St. Paul, from Albany, N. Y.
29. Brass sand, Northern Malleable Iron Works, St. Paul, from St. Louis, Mo.
30. Brass sand, Northern Malleable Iron Works, St. Paul, from Fort Snelling
32. Brass sand, Herzog Foundry, St. Paul, local, glacial drift

MESH OF SCREEN	46B	48B	51B	70A	75B	76B	77B	82B
4— 10	....	....	....	....	....	....	....	....
10— 20	.08	.08	....	....	....	....	....	....
20— 40	.30	.44	.71	.54	.22	.21	....	....
40— 60	.40	.64	.29	1.84	1.71	1.03	....	....
60— 80	.30	.40	.21	4.36	5.72	1.38	....	.04
80—100	.28	.46	.17	4.00	12.90	2.35	.12	.19
100—200	2.14	8.04	.46	20.28	43.83	18.66	2.27	6.02
200-silt	84.16	70.74	57.74	68.52	26.31	58.20	87.83	79.22
15-minute silt	2.00	3.00	19.31	......	1.02	1.03	4.13	2.09
30-minute silt	2.00	6.00	17.16	....	3.06	8.26	3.09	6.27
Clay	8.00	9.00	4.50	....	5.15	8.77	2.87	5.96
Total	99.66	98.80	100.55	99.54	99.92	99.89	100.31	99.79

46. Pocket of sand in laminated clay, North Minneapolis, glacial.
48. Pocket of sand in glacial drift, Lyndale Ave. S. and Minnehaha Drive, Minneapolis.
51. Pocket of sand in drift, Forty-sixth Street S. and Minnehaha Drive, Minneapolis.
70. Brass sand shipped in to Minneapolis, source unknown.
75. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.
76. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.
77. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.
82. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.

Mesh of Screen	84B	86B	111B	124B	208B	210B	211B	212B	213B
4— 10	....	.40	....	....	....	....	....	....	....
10— 20	2.04	.42	....	....	....	....	....	....	.72
20— 40	6.02	1.16	.06	1.10	.14	1.30	1.56	.60	1.98
40— 60	8.48	1.75	.04	3.16	.68	1.82	1.34	.52	1.74
60— 80	3.36	1.68	.18	5.94	4.74	2.54	3.00	1.64	3.48
80—100	2.80	1.43	.20	3.10	4.18	1.88	3.28	1.02	3.96
100—200	7.21	3.78	1.16	3.02	4.82	8.96	9.78	3.26	8.56
200-silt	24.77	56.65	59.86	64.74	72.50	67.04	60.68	62.64	59.92
15-minute silt...	7.54	6.52	4.56	2.30	3.84	4.68	5.96	7.36	4.10
30-minute silt...	23.69	17.16	12.00	6.00	5.22	7.08	9.00	15.02	7.18
Clay	13.64	9.04	19.12	9.00	2.64	3.74	5.90	6.14	5.80
Total	99.65	99.99	97.18	98.36	98.76	99.04	100.50	98.20	97.44

84. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.
86. Loess, Pilot Knob, near Mendota, upland.
111. Loess, brass sand, 10 miles northwest of Red Wing, upland, 400 ft. above river.
124. Loess, brass sand, 1 mile northwest of Nerstrand, Rice County.
208. Loess, brass sand, Clay Bank station, Goodhue County.
210. Brass sand, from Albany, N. Y., University of Minnesota, foundry.
211. Brass sand, St. Paul Brass Founding Co., from "southern Minnesota."
212. Brass sand, St. Paul Brass Founding Co., obtained locally.
213. Floor sand, brass, Commutator Company, Minneapolis.

Mesh of Screen	214B	217B	221B	239B	260B	261B	295B	296B	297B
4— 10	....	....	....	....	....	....	....	....	....
10— 20	....	....	.12	....	2.22	....	....	....	....
20— 40	.14	1.32	.34	.10	2.84	....	....	1.42	.24
40— 60	.00	1.44	1.54	.12	2.44	.32	.14	12.70	4.24
60— 80	.24	5.56	.26	.18	1.22	.36	.24	17.46	4.84
80—100	.12	5.86	2.82	.20	2.22	1.00	.34	13.29	4.14
100—200	.22	18.26	38.42	1.54	21.60	16.34	4.14	30.79	38.48
200-silt	65.62	56.22	45.82	75.34	56.92	60.00	68.14	9.90	28.09
15-minute silt...	10.06	1.26	.88	5.48	.16	3.08	9.30	8.80	2.16
30-minute silt...	12.92	4.34	4.76	9.90	4.78	7.48	13.48	1.96	3.53
Clay	9.86	4.82	4.30	4.00	3.96	10.56	4.36	3.60	13.44
Total	99.18	99.08	99.26	96.86	98.36	99.14	100.14	99.92	99.16

214. Brass sand, Commutator Company, Minneapolis, source unknown.
217. Floor sand, brass, Twentieth Century Brass Company, Minneapolis.
221. Brass sand, Commutator Company, Minneapolis, Albany, N. Y.
239. Loess, brass sand, Farmington, Dakota County, Minn.
260. Floor sand, brass, Soo Line Railway Shops, Minneapolis.
261. Brass sand, Soo Line Railway Shops, Albany, N. Y.
295. Brass sand, from Milwaukee, Flour City Ornamental Iron Company, Minneapolis.
296. Brass sand, from Milwaukee, Flour City Ornamental Iron Company, Minneapolis.
297. "French sand," imported from France, Flour City Ornamental Iron Company, Minneapolis; facing sand, ornamental work.

MECHANICAL AND MINERAL ANALYSES OF LOAMS

The laboratory results of the mechanical analysis of foundry loams are recorded in Table XII. Forty-five samples of loam were collected and subjected to mechanical analysis, by both dry and wet methods. The thirty-four analyses recorded in Table XII are selected from the list and are representative. The results by the wet method "B" only are given.

The thirty-four analyses recorded in Table XII include three types of material: (a) the raw unused loams taken from the stock bins of the foundries, which were used in making facing sands and floor sands, and for doctoring floor sands; (b) floor sands in actual use, which consist of mixtures of sands, loams, coal screenings (sea coal), etc., and which had been used one or more times; and (c) facing sands, which are mixtures similar in type to the floor sands, but more carefully prepared, and represent approximately, in so far as texture and clay content are concerned, the constitution sought in foundry loams.

The texture of the facing sands, floor sands, and loams is indicated in a general way by the "comparative mesh" in Table XII. For the facing sands the mesh ranges from 49 to 69, and the clay content ranges from 4.56 to 5.64 per cent. For the floor sands the mesh ranges from 46 to 90, with a clay content of 2.52 to 5.30 per cent. For the raw unused loams the mesh ranges from 33 to 250, with a clay content of 4.56 to 10.98 per cent.

Some of the floor sands were used without facing sand and others with facing sand, and in comparing them the grade of work should be taken into account. The most noticeable difference in the floor sands for heavy and for light work is seen in the mesh of the sand; the mesh of the sand for heavy work is 62 and 65, in sands 222 and 257, and the mesh for light work is 82 and 85 in sands 223 and 258.

In the 18 samples of fresh, or raw, loam collected in the foundries, the analyses of which are recorded in Table XII, the clay content ranged from 4.56 to 10.98 per cent. Some of these loams were used directly in molding without the addition of other materials, but most of them were used for "doctoring" the floor sands; that is, a little of the raw loam was added from time to time to the floor sand to replenish the clay as the bond was destroyed by repeated use; and for this purpose loam carrying an excess of clay is preferred since a less amount of new loam is required to bring the clay content to normal. The silts in these 18 samples ranged from 6.10 to 22.72 per cent.

All of the loams listed in Table XII were obtained in or near the cities of Minneapolis and St. Paul. Most of the loams were furnished the foundries by dealers in sands and loams. In Minneapolis practically all of the loam was obtained in the northeast part of the city, known as Columbia Heights, where the loam occurs as a mantle 2 to 6 feet deep, overlying the glacial drift, which forms a succession of small rounded knolls with intervening basins or kettle holes, that make the moraine of the last glacial period.

This loam is subject to wide variations in character within distances of a few rods laterally, and varies also from the surface downward, so that it is all but impossible to obtain a uniform product by the method of pitting it. A uniform product might be obtained by taking large batches and machine mixing the batch by the aid of a sand elevator and a series of riddles. In the absence of such mixing the loam requires close attention and repeated tests to know the actual constitution.

In St. Paul the loam occurs in the same relation, viz., mantling the glacial drift, and is obtained at numerous places, there being no well-defined or preferred area. In fact a considerable part of this loam is supplied by contractors making excavations for building foundations, who deliver to the foundries any material having the general appearance of loam that will pass inspection at the foundry.

In the vicinity of St. Paul and Minneapolis glacial drift of two periods is present. The upper or younger drift varies greatly in character from place to place, is essentially clayey in constitution, and rarely serviceable for foundry purposes. Beneath this young drift is an older deposit known as the Early Wisconsin, or red drift, which is less clayey and less variable in character. This red drift consists essentially of coarse sand with a moderate clay content, and in places very little gravel. A fair example of this material is shown in sample 254. Small amounts of this material were observed in a few foundries, having been provided by contractors as above noted. This material is worthy of a careful test by the foundries, since the clay it contains is more refractory than the clays in the surface loams, the body of the material is coarser, and in its natural state more nearly conforms to the requirements of molding loams.

Sample 163, Table XIV, was collected at Bellechester, Goodhue County, 20 miles by rail south of Red Wing. Extensive pits are operated here, mining a semi-refractory clay (Cretaceous) for the Red Wing potteries. Interbedded with this clay are thin beds of sand which are carefully separated from the clay and piled by means of cable and drag line in immense dumps. Sample 163 is a sample of one of the dumps representing hundreds of thousands of tons. This material is worthy of a careful test in the foundries because: (a) the clay in the sand is as refractory as any in the state; (b) the sand is nearly all quartz and well proportioned; (c) it is a waste, or by-product of the clay-mining and could be loaded on the cars at the same expense that it is piled in the dump, since the drag line runs over the gondolas for loading the clay; (d) the product would be more nearly uniform than the local loams now in use. It will be observed that by analysis 163, Table XIV, compares favorably with 22, Table XII, which is a synthetic sand and supposedly is correctly proportioned.

Synthetic sands and loams.—It might seem that synthetic sands offer the solution to the problem of foundry loams; that is, if carefully sized quartz sand were mixed with just the right proportion of good clay a loam could be made that would exactly meet the molding requirements. But when it is recalled that as soon as the loam is used in founding the clay is burned to some extent, and with each repeated use the clay bond still further deteriorates, it is apparent that no matter how carefully prepared originally, the sand rapidly changes in physical constitution with use. Not only is the clay destroyed as such, but the burned clay and burned sand become dead, silty material that does not function in the granulation, but serves instead to clog the interstitial spaces in the sand, interfering with the permeability. Synthetic sand therefore deteriorates with use, and sooner or later requires doctoring to replenish the bond, and to offset the silty material that gradually accumulates with use. A carefully proportioned synthetic sand rapidly approaches a constitution having the same objectionable features as natural loam.

The feasibility of synthetic sand resolves itself into a question of costs. If natural sands or loams, that approach somewhat closely the requirements, can be obtained it is usually cheaper to use these, bringing them to the standard by doctoring them at the beginning, rather than to build up the entire body by carefully proportioning several sands and clays. If natural sands or loams can be obtained the clay content of which is refractory, or semi-refractory, with the sand itself also refractory, the need for doctoring will be reduced to the minimum, and a long lived sand secured. In the light of present foundry practice this seems the more likely solution of the problem.

The clay content of each sample of loam is shown in Table XII. This is mechanically separated and not all of it is necessarily the mineral kaolinite, though much kaolinite is present. The minerals of the coarser portions were determined in five different loams. The quartz content of the portions examined ranges from 67 to 90 per cent. Feldspar is the most abundant mineral, next to quartz; and in the coarser sands, fragments of igneous rocks consisting of two or more minerals make up as much as 11.7 per cent of the sand. The figures for iron oxide include only grains of that material, and do not include coatings on grains. The amount varies from .27 to 1.61 per cent.

No extensive experiments were carried on to determine the effect of mineral composition on bonding power and refractoriness. The fact that all the sands except 254, which is a field sand, are being used successfully for some type of foundry work, indicates that aside from the clay content, the mineral composition within the limits shown is of minor importance.

TABLE XII. MECHANICAL ANALYSES OF LOAMS

Mesh of Screen	2	3	6	7	17	17x	22	23
4— 10	....	....	....	....	3.62	....	.14	.48
10— 20	.82	.86	.54	.12	4.88	.70	.70	6.52
20— 40	6.98	5.74	5.82	5.44	16.32	2.08	5.70	15.28
40— 60	18.74	14.10	8.46	15.52	12.62	3.51	13.78	10.12
60— 80	7.40	6.08	12.90	22.00	14.70	1.73	24.12	11.22
80—100	6.10	4.22	6.66	5.30	8.44	1.64	20.00	6.92
100—200	15.46	10.98	10.48	9.30	12.06	7.67	15.00	9.18
200-silt	32.08	38.00	32.26	22.80	14.40	62.12	4.38	17.50
15-minute silt	2.32	2.00	4.92	3.34	1.16	4.39	.38	1.52
30-minute silt	4.44	6.00	6.88	5.52	4.94	9.87	5.14	6.76
Clay	5.02	10.80	9.96	9.32	6.18	6.24	11.42	10.12
Total	99.36	98.78	98.88	98.66	99.32	99.95	100.76	95.62
Comparative mesh	79	98	111	85	44	214	70	52

2. Floor sand, University of Minnesota, foundry, grey iron work.
3. Loam, raw, University of Minnesota, foundry, local, glacial.
6. Loam, raw, Eagle Foundry, Minneapolis, local, glacial, grey iron.
7. Loam, raw, Gas Traction Foundry, Minneapolis, local, glacial, grey iron.
17. Loam, raw, Valley Iron Works, St. Paul, grey iron, heavy work, local.
17x. Loam, raw, Valley Iron Works, St. Paul, grey iron, light work, local.
22. Synthetic sand; mixture of sands 19, 20, and 21, ratio 1:1:6.
23. Loam, raw, American Hoist & Derrick Co., St. Paul, grey iron, heavy work.

Mesh of Screen	24	27	33	222	223	224	225	226
4— 10	....	.60	8.40	.10	....	.06	.94	.24
10— 20	.12	1.00	5.56	2.02	1.20	.76	1.70	.92
20— 40	1.60	4.76	12.84	9.64	7.22	3.60	7.26	3.08
40— 60	1.42	3.40	9.66	12.56	8.96	1.98	6.76	2.14
60— 80	2.88	3.38	9.78	16.46	13.98	3.48	10.52	3.12
80—100	3.06	1.92	6.02	11.56	8.24	2.22	6.52	1.96
100—200	11.32	3.32	9.62	14.50	12.32	4.12	11.98	3.26
200-silt	59.12	48.28	17.80	22.14	35.54	50.14	31.44	51.48
15-minute silt	5.54	7.12	2.82	1.56	1.46	8.02	3.88	7.62
30-minute silt	8.40	15.60	9.02	4.60	5.10	14.16	8.86	14.60
Clay	5.52	10.98	8.38	4.00	2.88	10.80	10.00	8.98
Total	98.98	100.36	99.90	99.14	96.90	99.34	99.86	97.40
Comparative mesh	230	145	36	62	82	210	77	200

24. Loam, raw, American Hoist & Derrick Co., St. Paul, grey iron, light work.
27. Loam, raw, Northern Malleable Iron Works, St. Paul, light work.
33. Loam, raw, Herzog Foundry, St. Paul, grey iron.
222. Floor sand, Minneapolis Steel & Machinery Co., grey iron, heavy work.
223. Floor sand, Minneapolis Steel & Machinery Co., grey iron, light work.
224. Loam, raw, Minneapolis Steel & Machinery Co., grey iron, local.
225. Loam, raw, Minneapolis Steel & Machinery Co., grey iron, local.
226. Loam, raw, Minneapolis Steel & Machinery Co., grey iron, local.

MESH OF SCREEN	227	240	241	242	254	255	256	257	258
4— 10	....	1.52	.20	3.70	6.08	....	....	....	....
10— 20	7.06	1.34	.62	1.22	11.00	.24	1.58	1.30	.76
20— 40	20.72	2.98	2.00	2.54	20.52	2.48	6.70	9.54	6.06
40— 60	12.28	5.68	6.32	6.78	11.10	8.34	8.20	22.86	10.26
60— 80	14.16	13.20	22.90	14.72	12.94	4.74	9.40	9.52	16.32
80—100	6.34	14.74	16.66	14.36	6.40	3.98	7.20	5.92	6.22
100—200	9.20	27.52	24.88	25.86	9.78	9.30	8.98	11.42	18.76
200-silt	14.40	21.80	18.62	21.46	10.52	48.24	36.00	25.74	27.04
15-minute silt...	2.26	1.70	1.32	1.38	2.00	4.52	5.02	2.38	2.40
30-minute silt...	6.52	3.62	2.56	3.38	4.52	8.44	7.86	5.24	7.08
Clay	7.70	2.52	3.40	4.12	4.56	9.76	10.98	5.20	5.36
Total	100.64	96.62	99.48	99.52	99.42	100.04	101.92	99.12	101.22
Comparative mesh	49	68	90	55	33	183	57	65	85

227. Loam, raw, Minneapolis Steel & Machinery Co., grey iron, St. Paul.
240. Floor sand, Northern Malleable Iron Works, St. Paul. light.
241. Floor sand, Northern Malleable Iron Works, St. Paul. light.
242. Floor sand, Northern Malleable Iron Works, St. Paul. light.
254. Loam, raw, old red drift, 1349 Central Avenue, Minneapolis, field sample.
255. Loam, raw, Crown Iron Works, Minneapolis, grey iron work. local.
256. Loam, raw, Crown Iron Works, Minneapolis, grey iron work, local.
257. Floor sand, Crown Iron Works, Minneapolis, grey iron work, heavy.
258. Floor sand, Crown Iron Works, Minneapolis, grey iron work, light.

MESH OF SCREEN	259	266	267	268	269	270	271	272	273
4— 10	....	....	....	....	....	....	....	.40	3.54
10— 20	.46	6.70	8.38	5.00	5.40	6.80	1.30	1.40	4.94
20— 40	10.32	21.60	21.04	14.34	17.10	22.30	2.40	3.88	13.84
40— 60	12.06	21.68	24.06	23.00	27.94	23.06	6.90	5.30	15.70
60— 80	21.58	6.06	5.82	6.34	6.60	5.98	3.47	2.40	5.64
80—100	12.78	4.06	4.70	5.08	5.20	4.06	2.68	2.56	4.08
100—200	12.24	9.36	10.48	11.88	11.34	8.96	10.04	9.10	9.88
200-silt	18.10	16.46	15.38	21.68	15.84	15.80	51.90	48.40	22.64
15-minute silt...	2.18	1.50	1.24	1.88	2.18	1.44	3.72	4.96	2.88
30-minute silt...	4.52	7.28	4.64	5.28	.00	5.98	9.92	8.64	7.28
Clay	4.56	5.92	4.26	5.30	4.76	5.64	8.84	8.72	8.86
Total	98.80	100.62	100.00	99.78	96.36	100.02	101.17	95.76	99.28
Comparative mesh	69	49	46	55	50	49	175	142	47

259. Facing sand, Crown Iron Works, Minneapolis, mixture, loam, sand, coal.
266. Facing sand, American Brake Shoe Co., Minneapolis, mixture, loam, sand, coal.
267. Floor sand, American Brake Shoe Co., Minneapolis, backing sand, grey iron.
268. Floor sand, American Brake Shoe Co., Minneapolis. light work, grey iron.
269. Facing sand, American Brake Shoe Co., Minneapolis, mixture, loam, sand, coal.
270. Facing sand, American Brake Shoe Co., Minneapolis, mixture, loam, sand, coal.
271. Loam, raw, American Brake Shoe Co., Minneapolis, grey iron work, local.
272. Loam, raw, American Brake Shoe Co., Minneapolis, light work, grey iron.
273. Loam, raw, American Brake Shoe Co., Minneapolis, heavy work, grey iron.

MINERAL ANALYSES OF LOAMS

NUMBER	17	254	272	273	Kerrick
Part examined (over 200-mesh)	72.6%	77.82%	26.04%	80.2%	96%
Quartz	70.69	67.91	83.04	73.04	90.1
Feldspar	11.95	15.53	9.87	14.18	7.01
Igneous rock	11.71	11.11	1.43	6.30	....
Hornblende	1.72	2.40	2.64	2.83	.46
Diopside	1.14	.56	....	....	....
Iron oxide	1.02	.91	.27	1.61	.72
Chalcedony	.37	....	....	....	....
Augite	.27	.73	1.52	.66	.47
Tremolite	.13	....	....	....	....
Magnetite	.09	.06	.07	.17	.04
Biotite	.02	....	....	....	.01
Tourmaline	.01	.01	.05	.01	....
Zircon	.01	....	.01	.01	....
Bronzite	.01	....	....	....	....
Chlorite	....	.72	....	.43	....
Serpentine	....	.02	....	....	....
Garnet	....	.01	....	....	....
Dolomite	....	....	....	.54	....
Slate	....	....	....	.12	....

CLAYS

Clay is a naturally occurring physical mixture of various products of rock-weathering in a very fine state of division, the individual particles of which range from about .005 millimeter in diameter to submicroscopic. The chief physical properties of clay are plasticity when wet; large absorptive power of water attended by swelling of the mass and the evolution of heat; absorption of gases and coloring matter; shrinkage on drying attended by absorption of heat; cohesive power in plastic state; and great tensile strength when dry. The constituents, as determined by chemical analysis, show a preponderance of kaolinite or some other hydrous silicates of alumina commonly considered essential.

In classifying clay according to its uses, Ries[11] cites 47 distinct uses made of clay in the industries and arts. The material used for these various purposes has come to be called clay, in common parlance, regardless of whether it is a pure mineral, or consists largely of impurities or inert material. In fact kaolinite rarely occurs in nature in the pure state; it nearly always occurs mixed with inert material or impurities such as sand and other rock fragments finer than sand, commonly called silts. Accordingly we have brick clays, potters' clay, china clays, modeling clays, etc.

Pure clay as such could not be used in most of the industries in which so-called clay is employed. Brick clays may carry less than 5 per cent of kaolinite, the remaining 95 per cent being inert material,

[11] Ries, H., Economic geology, p. 182, 1916.

principally sand and silt. Sample 59, Table XIII, shows by mechanical analysis only 1.5 per cent of the finest grained material, yet it is used for making brick.

The materials used in ceramic work under the name of clay commonly contain less than 50 per cent of kaolinite, but the other inert material present is just as essential as the true clay, so that it is not strange that the term clay is used to designate the heterogeneous mixture. By common consent any material that will develop a certain degree of plasticity is called clay in most of the industries using clay.

Colloidal material in clays.—It has long been known that certain substances in solution will diffuse through membranes whereas other substances will not, also that the same substance may be in such a state that it will diffuse through a membrane or it may be in such a state that it will not. Substances in the solutions that will not diffuse through a membrane are said to be in a colloidal state. Some substances exist under certain conditions in the colloidal and under other conditions in the non-colloidal state.

Colloidal materials may be organic or inorganic. The organic colloids include such common materials as jellies, albumen, gelatin, agar, and compounds of humic acid. The inorganic colloids include such common substances as silicic acid, ferric hydrate, and aluminum silicate. The colloidal state may be simply a matter of the fineness of division of the particles. It is thought that any substance can be brought into the colloidal state if it can be reduced to fine enough individual particles.

It is known that most, if not all, clays contain colloidal material, but the per cent of colloidal material in clay is small, rarely more than 3 per cent, and usually much less. The colloidal material in clay may be silica, alumina, ferric iron, or other inorganic material, or it may include organic material also.

It is thought by some investigators that the plasticity of clays is dependent on the colloidal material present in the clay, and that the absorptive power of clay for water and for coloring matter is also dependent on the presence of colloidal material. Moore, Fry, and Middleton[12] found that true clay, as well as clay soils, absorb coloring matter in direct proportion to the amount of colloidal material present.

Plasticity of clays.—Plasticity is that property in a material which enables it to change form without rupture, the new shape being retained when the deformitory force is removed. The cause of plasticity has not been satisfactorily explained. Some clays are much more plastic than others. Some clays that are of low plasticity develop greater plasticity under certain kinds of treatment, such as grinding, or weathering.

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[12] Moore, C. J., Fry, W. H., and Middleton, H. E. Methods of determining colloidal matter in soils: Journal of Industrial and Engineering Chemistry, Vol. 13, 1921.

Clays that are richest in kaolinite are seldom as plastic as those that are not so pure. Plasticity does not appear to be connected with chemical composition, yet on heating to temperatures of 415° to 600° C. all clays lose their plasticity, and it can not be restored. It has been urged that plasticity is due to the shape of the clay particles, and there is some evidence in support of this claim, but the hypothesis remains unproved. Plasticity has been increased by bacterial inoculation, but it has not been proved that bacterial action is the cause of plasticity.

Whatever its nature and origin, it is fairly well established that many of the properties of clay are closely connected with the colloidal matter present, such matter being in the form of a film of colloidal gel surrounding particles of non-plastic inert nature.

Tensile strength of clays.—Tensile strength, or the resistance to torsional stresses, or to rupture in clays is influenced by the plasticity of the clay, the size and shape of the inert non-plastic grains in the mass, and the amount of colloidal material present.

In the mechanical analysis of molding sands, loams, and foundry clays, the material that would remain in suspension in distilled water 24 hours after deflocculation with ammoniated water, was called clay. No attempt was made to determine the amount of colloidal material present in this clay. The tensile strength developed in the molding sand, as shown by the briquet tests, varies with the proportion of clay present, but is not in direct ratio, that is, the same per cent of clay gives greater tensile strength in some sands than in others. In the same type of material, that is, material of the same origin, or from the same source, the tensile strength is approximately in proportion to the per cent of clay present.

The variation in the tensile strength may be due to the variation in the amount of colloidal material present in the different samples, or it may be due to differences in the sand, that is the proportioning of the fine and coarse sizes, the shape of the grains, etc. On the whole it seems more probable that the difference in tensile strength is due to differences in the clay itself in the different samples, which in turn suggests that the variation in the amount of colloidal material present in the different samples is the real cause of the difference in tensile strength. Much more detailed experiments would be required to obtain data on which a conclusion might be based.

Mechanical analysis of clays.—The results of the mechanical analysis of the so-called clays are recorded in Table XIII. Of the 17 analyses there recorded, 4 are analyses of clays collected in the foundries and 13 were samples collected in the field in different parts of the state, and used as clay for manufacturing purposes, or were material suitable for such use.

The clays collected in the foundries were used for various purposes, such as daubing cupolas, patching the lining of steel furnaces, doctoring burned out molding sand, and for making synthetic molding sand. The content of clay in the 17 samples as shown by Table XIII, ranges from 1.5 to 69 per cent. Comparing Table XIII with Tables IX, X, XI, XII, and XIV, it will be observed that many of the so-called sands and loams carry a larger per cent of "clay" than some of the samples listed in Table XIII, as clay. Even the St. Peter sand carries a larger per cent of "clay" than sample 59, Table XIII, which is a brick "clay."

The value of so-called clays for certain foundry purposes is roughly proportional to the per cent of clay present. Material that shows 20 per cent of clay is worth about twice as much as material that shows 10 per cent of clay, and the price paid for the material should be graduated accordingly.

Of the 17 clay samples listed in Table XIII, 8 came from the Cretaceous formation either directly or indirectly. They are numbers 10, 20, 129, 130, 132, 150, 164, and 171. They show a content of clay ranging from 28 to 69 per cent. Sample 265, supposed to be of more than ordinary refractoriness, showed a clay content of 37.02 per cent. This clay was imported from some other state, its original source was not learned.

Sample 164 was collected at Bellechester, Goodhue County, Minnesota, from the pits where clay was being mined for the Red Wing potteries. Several grades of clay are mined in this locality, but samples were not taken of all. Sample 164 does not fairly represent all the clays here found.

Sample 150, which had the highest proportion of clay, was collected a few miles north of Rochester, Olmstead County, Minnesota, from the glacial drift. A small mass of Cretaceous clay was here found in the drift, having been picked up by the glacier and incorporated without mixing with the foreign material. It is of no commercial value in itself, but is of interest in showing that deposits of exceptionally good clay occur in the region over which the glacier passed. It is within the range of possibilities that a systematic search might locate them.

Sample 130 was collected 2 miles east of Austin, Minnesota, 8 miles north of the Iowa line, from an outcrop of the Cretaceous.

Samples 45, 53, 58, and 59 were collected in North Minneapolis, in the Mississippi Valley above the falls, to illustrate the type of clays that occur here in considerable areas. It is improbable that this clay would be of much service in foundry work, since it carries a large percentage of lime, and other fluxes.

Clays similar in character occur at numerous points in the valley of the Minnesota River from Mankato northward to St. Paul, a distance of 100 miles. The type is illustrated by sample 180, which was collected at Chaska, Scott County, where it is extensively used in the manufacture of common brick.

In a previous investigation of Minnesota clays,[13] samples were collected and analyzed from the same localities as those of interest in foundry work. They serve to indicate in a general way at least, the probable composition of the clays listed in Table XIII.

The clays used in the Red Wing potteries[14] came from Bellechester and Clay Bank, Goodhue County, and may be taken as probably similar to, if not the same as, 164 given in Table XIII. Three analyses of these clays show the sodium oxide, magnesia, lime, and iron oxides, amounting to 5.59 to 6.04 per cent. It is probable that samples 10, 20, 129, 130, 132, and 150 would show upon analysis about as much of these fluxing constituents. Similarly, a sample of clay from North Minneapolis shows 18.73 per cent of potash, soda, lime, magnesia, and iron oxides. This is from the same locality as samples 58 and 59, and is probably the same type of material. It is probable that samples 45, 55, and 180 would show upon analysis a similar composition. From these analyses it will be seen that the glacial clays carry more than three times as much of the alkalies, iron oxides, and magnesia as do the Cretaceous clays, and they are probably correspondingly less refractory.

TABLE XIII. MECHANICAL ANALYSES OF CLAYS

Mesh of Screen	10X	20	45	53	58	59	129
4— 10	....	....	....	....	....	....	....
10— 20	.26	.90	....	....	.74	....	1.32
20— 40	.44	2.00	....	....	.94	....	2.52
40— 60	.32	3.60	....	....	.24	....	1.94
60— 80	.50	2.22	1.04	.20	.24	....	.70
80—100	.28	1.80	2.08	.18	.16	.14	.58
100—200	.80	3.46	.56	1.16	.62	4.52	1.34
200-silt	18.72	12.38	57.20	84.98	20.20	84.00	9.10
15-minute silt	1.62	2.76	10.40	3.24	5.00	2.00	2.58
30-minute silt	19.98	22.00	22.88	4.32	47.00	5.00	22.24
Clay	54.00	48.26	5.82	5.42	24.00	1.50	58.26
Total	96.92	99.38	99.98	99.50	99.14	97.16	100.58

10. Gas Traction Founding Co., Minneapolis, used in steel work, furnace, came from Ottawa, Minn. Cretaceous, furnace lining, and molding.

20. American Hoist & Derrick Co., St. Paul, came from Ottawa, Minn. Cretaceous, used in molding sand, and for furnace work.

45. River clay, North Minneapolis, City Work House, clay pit.

53. Glacial clay, Minnehaha Creek and Lyndale Avenue, Minneapolis

58. Marshall Avenue and Twenty-ninth Street N., Minneapolis, six feet below street.

59. Marshall Avenue and Thirty-fourth Street N., Minneapolis, brick yard.

129. Ottawa, Minn., sample furnished by Ottawa Sand Co.

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[13] Grout, F. F. Bulletin, Minnesota Geological Survey, No. 11, 1914.

[14] Analyses by Grout. *Op. cit.*

TABLE XIII. MECHANICAL ANALYSES OF CLAYS—*Continued*

Mesh of Screen	130	132	150	164	171	180	253
4—10	.18	......	......	......	......	......	.48
10—20	.18	.60	......	.26	......	......	1.44
20—40	.14	1.72	......	.54	.24	......	4.52
40—60	.16	.86	.18	.14	.34	......	8.24
60—80	.28	1.16	.32	.14	.18	......	3.52
80—100	.37	1.70	.54	.50	.20	50.20	2.36
100—200	1.88	10.10	.90	7.72	.44	......	6.16
200-silt	11.86	23.06	1.48	32.38	11.88	......	36.22
15-minute silt	3.96	.98	7.70	4.60	4.12	11.28	6.28
30-minute silt	12.00	16.00	21.24	23.06	35.68	18.34	13.50
Clay	67.14	36.02	69.32	27.96	45.08	20.68	17.46
Total	98.15	92.20	101.68	97.28	98.16	100.50	100.18

130. Cretaceous outcrop, two miles east of Austin, Minn.

132. Cretaceous outcrop, bank of Iowa River, one mile above Le Roy.

150. Lens of clay in glacial drift, near Rochester, derived from Cretaceous.

164. Bellechester, Goodhue County, Minn., clay pit of Red Wing, potteries, Cretaceous.

171. Ottawa, Minn. clay pits, Cretaceous clay in pot holes in surface of Jordan formation.

180. Chaska, Carver County, Minn., Minnesota River Valley clay used for common brick, glacial.

253. Eagle Foundry, Minneapolis, local clay loam, glacial, used in daubing cupola, locality unknown.

Mesh of Screen	265	274	275
4—10	1.03	......	......
10—20	.62	......	.48
20—40	1.10	.50	2.60
40—60	2.84	2.44	9.04
60—80	1.44	2.20	5.44
80—100	1.44	1.84	4.40
100—200	4.84	7.10	12.48
200-silt	10.74	41.80	46.40
15-minute silt	5.64	4.38	3.46
30-minute silt	28.36	9.44	6.58
Clay	37.02	28.38	7.08
Total	95.07	98.08	99.46

265. American Brake Shoe Company, Minneapolis, imported clay, semi-refractory, used for furnace and molding.

274. Columbia Heights, Minneapolis, clay loam, furnished to foundries, extra heavy.

275. Columbia Heights, Minneapolis, ordinary loam, as furnished to foundries.

Samples 274 and 275 are included in Table XIII for purposes of comparison. These samples were collected in one of the pits at Columbia Heights, Minneapolis, which furnish loam to the foundries. Sample 274 is a fair average of the type of material here found. This sample is from a lenslike horizon of clay loam occurring in the main bed. It will be observed that 275 carries more clay than the glacial or river clays above described, i.e., 45, 53, and 59, and at the same time is not rated as clay—illustrating the confusion of terms.

TABLE XIV. MISCELLANEOUS SANDS

Mesh of Screen	4B	14B	25A	61	97	139	141	158
4 — 10	.61	....	26.00	....	....	....	....	....
10 — 20	.96	.68	29.50	.80	....	....	....	....
20 — 40	7.78	4.36	31.00	10.06	....	....	.40	.96
40 — 60	23.74	13.30	7.80	22.24	....	....	.56	1.10
60 — 80	5.58	15.16	2.80	32.54	....	.80	.82	4.22
80 — 100	6.02	14.36	1.00	14.44	....	.36	.66	8.76
100 — 200	13.06	37.22	1.60	8.73	1.50	31.88	5.70	30.00
200-silt	28.94	9.90	1.10	3.20	75.20	51.70	50.00	46.00
15-minute silt	1.88	1.00	....	.50	5.00	.18	12.00	Trace
30-minute silt	4.68	2.00	....	2.00	8.00	4.00	14.00	4.00
Clay	4.96	3.00	....	4.00	8.00	8.80	15.14	2.50
Total	98.21	100.98	100.80	98.51	97.70	97.72	99.28	97.54

4. Floor sand, Eagle Foundry, Minneapolis.
14. Wind blown glacial sand, East Hennepin Avenue, Minneapolis.
25. Blast sand, glacial, American Hoist & Derrick Co., St. Paul.
61. Dune sand, Fridley, Anoka County.
97. Dolomitic sand, 10 miles east of Cannon Falls.
139. Dolomitic sand, Fillmore County, 4 miles southwest, Wykoff.
141. Dolomitic sand, Spring Valley, Fillmore County.
158. Dresbach sand, Red Wing.

Mesh of Screen	161A	162A	163B	178B	181B	200B	205B	207B
4 — 10	18.24	.96	....	....	....	....	....	....
10 — 20	32.50	1.78	3.22	....	....	71.30	.30	....
20 — 40	27.20	20.12	30.62	....	....	25.28	8.80	....
40 — 60	9.84	43.92	18.48	....	....	.98	15.90	....
60 — 80	2.54	16.90	26.28	.10	.04	.58	25.92	....
80 — 100	1.96	7.56	9.70	.08	.16	.08	16.36	....
100 — 200	3.30	5.06	2.42	10.22	21.14	.10	16.66	.10
200-silt	3.86	1.96	.56	84.50	74.96	.16	9.76	61.62
15-minute silt	....	....	.24	1.50	2.24	.00	1.24	8.36
30-minute silt	....	....	.98	.62	.52	.48	2.98	24.70
Clay	....	....	8.76	.80	1.02	.62	1.56	3.88
Total	99.44	98.26	101.26	97.82	100.08	99.58	99.48	98.66

161. Cretaceous sand, Bellechester, Goodhue County.
162. Cretaceous sand, Bellechester, Goodhue County.
163. Mixed sands in dump, Bellechester, Goodhue County.
178. Silty River sand, Chaska, Carver County.
181. Silty River sand, Carver, Carver County.
200. Quartzite screenings, Jasper, Rock County, from crusher.
205. Quartzite screenings, Jasper, Rock County, from crusher.
207. Quartzite screenings, Jasper, Rock County, from crusher.

MINERAL ANALYSIS OF MISCELLANEOUS SANDS

NUMBER	61	158	163
Part examined (over 200-mesh)	99.66%	40.7%	97.5%
Quartz	89.05	98.841	96.54
Feldspar	9.51	.26	2.96
Limonite	.498	.003	.01
Hornblende	.489	....	.009
Kaolin	.192	....	....
Chlorite	.072	....	....
Diopside	.042	....	....
Magnetite	.038	.016	....
Rock	.008	....	....
Zircon	.005	....	....
Serpentine	.004	....	....
Tourmaline	.002	....	....
Spinel	.001	....	....
Garnet	.001	....	....
Mica	....	.49	....
Glauconite	....	.006	....

LABORATORY TESTS OF TENSILE STRENGTH

The laboratory work was guided to a large degree by the sand troubles encountered in the foundries visited, and was accordingly devoted to specific problems for the most part, rather than to systematic series.

Samples B 4, C 4, and D 4, all in Table XV, were collected in the same foundry, but from different sand piles. In this foundry the practice was to allow each molder to follow his own method of tempering the sand, and the purpose of the tests was to determine to what degree the personal equation of the molder was a factor in the tensile strength. The same raw sand was used by each molder. It will be observed that there was a variation of 50 per cent in the moisture content, of 15 per cent in the clay content, and a considerable variation in the tensile strength, in these three samples. The tensile strength in these three samples is not in proportion to the content of clay or of moisture. The maximum strength coincides with the minimum moisture and a medium clay content. Inasmuch as the same raw sand was used throughout the foundry, the variation in the clay content in the different piles is plainly due to doctoring the sands; that is, to the amount of raw sand added from time to time to replenish the bond as it is burned out, the amount so added varying with the individual molder.

Samples 240, 241, and 242 were collected in another foundry, but in the same manner as above described; that is, from separate heaps of sand in actual use for the same grade of work, and made by mixing the same original raw sands. In this instance, however, the sand for the entire foundry was tempered and riddled by one man whose business it was after closing hours, during the night, to prepare the sand for the following day. Even in this case, where exceptional care was exercised to obtain uniformity in the sand, at least in so far as riddling and tempering the sand was concerned, there was still a considerable variation in the moisture, in the clay content, and in the tensile stength, indicating the need of some simple and easy method of making accurate determinations of these factors from day to day. The problem in this instance was not regarded as serious, but it was recognized by the foundry management that there was a lack of uniformity in the grade of castings turned out, which was attributed to the sand used, and that the difficulty might be corrected if its nature could be discovered.

Samples 222 to 227, inclusive, were collected from still another foundry where the sand trouble presented a problem of a more serious nature, because of the loss from defective castings. In this instance sands 224, 225, 226, and 227 represent the raw sands, or loams, furnished the foundry. Samples 222 and 223 were floor sands in actual use, taken from the separate sand heaps, and molders' tables, and were made by mixing the loams 224, 225, 226, and 227 in varying proportions.

The sand did not stand up in the mold, in consequence of which blisters and blow holes appeared in the castings. The mechanical analysis of sand 222 showed a clay content of 4 per cent which should have afforded ample bond. The moisture, however, was abnormally low, viz., 3 per cent. The tensile strength was so low as to be negligible. Adding water in the laboratory up to 10 per cent in this sample failed to develop the required strength. The tensile strength of the raw sands 224, 225, 226, and 227, as the table shows, was ample. This seemed to indicate a burned out sand, and a failure to add enough raw sand to counteract the burning from repeated use. However, the presence of 4 per cent of clay in sample 222, according to the analysis, Table XII, does not appear to be in harmony with this suggestion.

A second visit to this foundry showed that the work here consisted in making large, rather massive, castings in grey iron and semisteel. It was necessary for the castings to remain in the flask for a considerable time before being shaken out, and the sand of the entire mold became heated excessively. Without allowing the sand to cool down to normal, or to rest, water was added to replenish that lost from evaporation and the operation was repeated. Under this treatment the clay which should serve as the bond had no opportunity to function.

Time is an important factor in developing plasticity in clay, which appears to have been disregarded in this case. The trouble might be ascribed to what may be called a fatigue of the bond. The most obvious remedy was the use of a larger volume of sand so that the sand might have a rest between each period of use, allowing the water to be absorbed by the clay.

Samples 200, 201, 205, and 207 give the results of an experiment with crushed quartzite to determine the effect of extreme angularity of grain on tensile strength. From the mechanical analysis of these samples, Table XIV, it will be seen that 200 is coarse, 205 medium, and 207 fine sand. Number 200, which showed a clay content of .62 per cent, did not develop a measurable amount of tensile strength. It is of interest to compare this sand with sand 5 from the St. Peter formation, in which the clay content is even less, but the sand grains are well rounded, and in which a tensile strength of 2.8 pounds was developed in the air-dried briquet.

The individual grains of quartzite screenings represent the extreme of angularity, a large proportion of the grains being long, sharp needles or elongated prisms. The experiment, while not elaborate enough to carry much weight, points to extreme angularity of grain as a disadvantage rather than an advantage in tensile strength.

A second experiment was tried to determine to what degree the tensile strength test could be depended on to reflect the varying content of bond. For this purpose a series of mixtures of sand 1 and sand 208 were used, ranging from 90 per cent of the former, and 10 per cent of the latter, to 10 per cent of the former and 90 per cent of the latter. The results are recorded in Table XV, in samples 229 to 237 inclusive. The clay content and tensile strength of samples 1 and 208, the components of the mixtures, are shown elsewhere in the table. It will be observed that the clay content is comparable in the two, but that the tensile strength is twelve times as great in 208 as it is in 1.

From Table XV it will be observed that the tensile strength increases quite uniformly with the increase of the proportion of sand 208 (loess) until 80 per cent of this sand is reached, after which the change is not appreciable.

DETERIORATION OF SAND WITH HEAT

It is well recognized that the bonding power of sand deteriorates with repeated use, and unless the sand is doctored by adding new raw sand, or clay, or some artificial bond, it soon becomes so weak that it will not stand up in the mold. In this condition it is said to be burned out.

When the liquid metal is poured into the mold the sand on the face of the mold is heated to temperatures approaching the temperature of the melt, which in brass and its alloys is 800 to 900 degrees F. and in cast steel is about 3,600 degrees F. Back from the face of the mold the sand is heated to progressively lower temperatures. But while the sand in the body of the mold is heated to moderate temperatures only, it nevertheless deteriorates in strength. By way of demonstrating this the following experiment was undertaken.

Three samples of loess were taken from samples 208 and labeled 283, 284, and 285. They were placed in an oven at room temperature and the oven raised to a temperature of 400 degrees C., or 752 degrees F., which temperature was maintained. At the end of one hour sample 285 was removed. At the end of two hours sample 284 was removed, and sample 283 was allowed to remain four hours. After baking, the samples were subjected to the wet method mechanical analysis to determine the amount of clay that would stay in suspension in water. Briquets were made from the material after tempering with water, and the briquets tested for tensile strength with the results shown in Table XV.

The clay content of the original raw material, loess 208, as shown above, is 2.64 per cent, and the tensile strength is 18.2 ounces. The tensile strength decreased in proportion to the length of time the material was baked, the decrease amounting to nearly one third in sample 283 after four hours baking. The clay content decreased also, amounting to nearly 35 per cent in sample 283, baked four hours; and less amounts for the other samples baked shorter periods.

A second experiment of the same nature was undertaken using two surface loams from Columbia Heights, viz., 274 and 275, renumbering them 286 and 287. Both samples were baked four hours at a temperature of 400° C., after which the clay content was determined by the usual method, and the tensile strength determined by briquets. The mechanical analysis of samples 274 and 275 are shown in Table XIII, from which it will be seen that sample 274 before baking showed a clay content of 28.38 per cent, whereas after baking four hours, as sample 286, Table XV, it showed a clay content of only 5.84 per cent, or a loss of 79 per cent.[15]

Sample 275, as will be seen from Table XIII, showed a clay content of 7.98 per cent, whereas after baking four hours, as sample 287, Table XV, it showed a clay content of only 4.26 per cent, or a loss of 46 per cent.

The effect of baking these loams was probably partially to dehydrate the clays, in consequence of which they lost some of their plasticity and were less effective as bond. The clay also lost in part the property of deflocculating when churned in ammoniated water, and hence would not stay in suspension.

The results of these experiments indicate that the mechanical method of determining the clay by suspension in ammoniated water gives an approximate measure at least of the amount of clay present that is effective as bond, and that the tensile strength test by means of briquets is at least an approximate measure of the amount of such clay present in the sample.

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[15] The term clay here used refers to the material that would stay in suspension in water 24 hours.

TABLE XV. TENSILE STRENGTH OF MOLDING SAND BRIQUETS

Laboratory Number of Sample	Moisture Content Per Cent by Weight	Clay Content Per Cent by Weight	Breaking Strength of Briquets			Nature of Sample and Conditions of Test
			Green	Air-Dried	Oven-Baked	
			In Ounces	In Pounds	In Pounds	
1	5	2.16	1.5	9		Core sand from St. Peter formation
B4	7	4.96	10.6	5.1	8.6	Floor sand from foundry
C4	10.5	5.12	7.8	10.8	42.9	Floor sand from same foundry as B4
D4	7.5	4.46	9.5	3.2		Floor sand from same foundry as B4
5	5	.05	1	2.8		Core sand from St. Peter formation
5A	5	1	3.4	5.0		Same sand as 5, clay added
5B	5	2.05	1.1	7.3		Same sand as 5, clay added
90	5	2.26	14.5	26.0		Sand from St. Peter formation, Cannon Falls
200	5	.62	0.0	1.0		Quartzite screenings, medium coarse
201	5	2.62	2.3	1.6		Quartzite screenings, 2 per cent clay added
205	5	3.56	2.0	1.86		Quartzite screenings, 2 per cent clay added
207	10	3.88	14.3	12.0		Quartzite screenings, very fine
208		2.64	18.2			Loess, from Clay Bank station, Goodhue County
222	3	4.0	.5	.2	.2	Floor sand in use, heavy founding
224	6	10.8	10.0	22.2	225.0	Loam, raw, used in foundry
225	6	10.0		15.0	17.7	Loam, raw, used in foundry
226	6	8.98		18.4	80.0	Loam, raw, used in foundry
227	6	7.7				
229	8	2.2 comp.	3.3			Mixture: 90 per cent sand 1, 10 per cent sand 208

TABLE XV. TENSILE STRENGTH OF MOLDING SAND BRIQUETS —*Continued*

Laboratory Number of Sample	Moisture Content Per Cent by Weight	Clay Content Per Cent by Weight	Breaking Strength of Briquets: Green, In Ounces	Air-Dried, In Pounds	Oven-Baked, In Pounds	Nature of Sample and Conditions of Test
230	5	2.24 comp.	5.0			Mixture: 80 per cent sand 1, 10 per cent sand 208
231	5	2.28 comp.	7.2		1.0	Mixture: 70 per cent sand 1, 30 per cent sand 208
232	5	2.33 comp.	8.1		1.5	Mixture: 60 per cent sand 1, 40 per cent sand 208
233	5	2.37	11.5		3.5	Mixture: 50 per cent sand 1, 50 per cent sand 208
234	5	2.43	14.9		3.0	Mixture: 40 per cent sand 1, 60 per cent sand 208
235	5	2.46	16.1			Mixture: 30 per cent sand 1, 70 per cent sand 208
236	5	2.52	17.6		16.9	Mixture: 20 per cent sand 1, 80 per cent sand 208
237	5	2.56	17.0			Mixture: 10 per cent sand 1, 90 per cent sand 208
240	7.7	2.52	8.7	7.2	14.7	Floor sand in use in foundry
241	7.0	3.40	6.1	12.7	17.0	Floor sand, same foundry as 240
242	8.1	4.12	8.8	8.9	13.5	Floor sand, same foundry as 240
257	12.0	5.20	10.3	13.3		Floor sand, in use in foundry, heavy work
258	9.2	5.36	17.00	22.00		Floor sand, in use for light work
259	8.5	2.56	10.77	17.2		Facing sand, mixture, grey iron work
260		3.96	9.25	2.2		Brass sand, used for heavy brass casting
266	8.4	3.92	8.5	7.7	2.0	Facing sand, mixture, grey iron work
267	7.5	4.26	7.5	1.5	Disintegrated in oven	Backing sand, in use in foundry, with 266

TABLE XV. TENSILE STRENGTH OF MOLDING SAND BRIQUETS—*Continued*

Laboratory Number of Sample	Moisture Content Per Cent by Weight	Clay Content Per Cent by Weight	Breaking Strength of Briquets			Nature of Sample and Conditions of Test
			Green	Air-Dried	Oven-Baked	
			In Ounces	In Pounds	In Pounds	
268	9.2	5.30	11.6	7.5	1.30	Floor sand, for light grey iron
269	9.4	4.76	5.7	4.0		Facing sand, for light grey iron
270	8.3	5.64	11.3	7.4	2.00	Facing sand, for grey iron work
283	10.0	1.72	12.8	3.7	1.6	Loess 208 after baking 4 hours
284	10.0	2.00	14.0			Loess 208 after baking 2 hours
285	10.0	2.20	16.0			Loess 208 after baking 1 hour
286	8.0	5.84	24.0	13.0	7.1	Loam 274 after baking 4 hours
287	8.0	4.26	24.0	12.0	7.4	Loam 275 after baking 4 hours
290	10.0	1.8	13.0	2.6	.60	Field sample
292		Molasses binder	24.3	16.3	0.0	Bronze sand, mixture 293 and 294
293		Molasses binder	21.0		0.0	Floor sand for bronze
296	8.0	3.6	5.0			Brass sand, from Milwaukee

TABLE XVI. PERMEABILITY TESTS

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
215 Standard sand	422	0	100	25	Standard sand, quartz, from Ottawa, Ill.; washed, dried, sized to 20 to 30 mesh
1 A	384	5	8.7	286	Core sand, molded, rammed hard, tested green
1 B	372	2*	14.4	173	Same cylinder as A, air-dried, tested dry
2 X	371	10	6.1	406	Floor sand, tempered, molded, rammed hard, tested green
2 Y	362.8	10	10.3	242	Floor sand, same as 2 X, rammed light, tested green
2 Z	363.1	10	8.9	280	Floor sand, same as 2 X, rammed medium, tested green
3 J	355	10	2.1	1,189	Loam, raw, tempered, molded, rammed hard, tested green
B 4 K	362	3.5	2.2	1,115	Floor sand as it came from foundry, rammed hard, tested green
C 4 K	355	2.0*	3.5	715	Floor sand, same as B 4 K tested after air dried
9 A	373	0	26.6	94	Fire sand, quartz, Massilon, Ohio, loose, dry, pestled
9 B		10	12.9	194	Fire sand, quartz, same as 9 A, molded, tested green
19	396	0	35.7	70	Quartz sand, raw, from Ottawa, Minn., dry, loose, pestled
21	410	5	7.6	327	Core sand, molded, tested green
200 A	311	0	78.1	32	Screenings, crushed quartzite, sized, 20 to 40 mesh, dry, loose
200 B	303	0	62.5	40	Screenings, crushed quartzite, sized, 40 to 60 mesh, dry, loose
200 C	315	0	73.5	34	Screenings, crushed quartzite, sized, 60 to 80 mesh, dry, loose
200 D	317	0	7.1	352	Screenings, crushed quartzite, sized, 80 to 100 mesh, dry, loose
208 A	356	0	1.3	1,944	Loess, from Goodhue County, Minn., loose, dry, pestled
208 B	363	10	13.9	180	Loess, same as A, molded, rammed hard, tested green
208 C	344	5*	10	250	Loess, same as B, air dried before testing
215	422	0	100	25	Standard sand, see head of list

* Indicates estimates or computations from incomplete data.

TABLE XVI PERMEABILITY TESTS—*Continued*

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
217 A	374		17.7	14*	Brass sand, molded, furnished by foundry
217 B			3.7	664	Brass sand, molded, furnished by same foundry
217 C			2.9	860	Brass sand, molded, furnished by same foundry
218 A			31.2	80	Core sand, same foundry as 217, made in cores by foundry, resin for binder
218 B			44.6	56	Same sand as A, core made at same foundry, different mixture of binder
220	398	0	100	25	Quartz sand from steel foundry, dry, loose
221 A	406	13	6.5	384	Brass sand, from Albany, N. Y., tempered in foundry, rammed light, tested green
221 B		7*	7.0	358	Brass sand, same as 221 A, air dried before testing
221 C	394	10	3.2	765	Brass sand, same foundry as A and B, source of sand local, tested green
222 A		0	16.6	150	Floor sand, grey iron work, loose dry sand
222 B	400	6	3.0	831	Floor sand, same as A, molded, tested green
222 C	364	3*	6.5	384	Floor sand, same as B, but air dried before testing
223 A		0.0	14.5	172	Floor sand, same foundry as 222, loose, dry
223 B	396	10.0	3.5	714	Floor sand, same as A, molded, tested green
224 A	350	0	12.2	204	Loam, raw, same foundry as 222 and 223, loose, dry
224 B	334	10	3.8	648	Loam, raw, same as 224 A, molded, tested green
224 C	334	10	1.3	2,020	Loam, raw, same as 224 A and B, rammed extra hard, tested green
224 D	301	0	3.2	776	Loam, raw, same as 224 C, kiln dried before testing

* Indicates estimates or computations from incomplete data.

TABLE XVI. PERMEABILITY TESTS—*Continued*

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
223-224 A	300	10	5.1	492	Mixture, 90% of floor sand 223 and 10% of loam 224, molded, tested green
223-224 B		10	5.0	498	Mixture, 80% of floor sand 223 and 20% of loam 224, molded, tested green
223-224 C	397	10	6.2	399	Mixture, 70% of floor sand 223 and 30% of loam 224, molded tested green
223-224 D	382	10	7.1	353	Mixture, 60% of floor sand 223 and 40% of loam 224, molded, tested green
223-224 E	346	10	8.0	311	Mixture, 50% of floor sand 223 and 50% of loam 224, molded, tested dry
225	377	10	8.0	314	Loam, raw, used, same foundry as 222, 223, 224, molded, tested green
226	383	10	9.0	277	Loam, raw, used with 224 and 225, same foundry, molded, tested green
227	438	10	9.8	255	Loam, sandy, used with 224, 225, and 226, same foundry, molded, tested green
228 A	398	0	100.0	25	Quartz sand, sized to 20 to 30 mesh, loose, dry, from Jordan and St. Peter formations
228 B	395	0	73.5	34	Quartz sand, sized to 30 to 40 mesh, loose, dry, from Jordan and St. Peter formations
228 C	393	0	39.6	63	Quartz sand, sized to 40 to 60 mesh, loose, dry, from Jordan and St. Peter formations
228 D	384	0	23.1	108	Quartz sand, sized to 60 to 80 mesh, loose, dry, from Jordan and St. Peter formations
228 E	381	0	13.0	192	Quartz sand, sized to 80 to 100 mesh, loose, dry, from Jordan and St. Peter formations
228 F	375	0	7.8	320	Quartz sand, sized to 100 to 200 mesh, loose, dry, from Jordan and St. Peter formations
240 A	358	0	1.2	2,027	Floor sand, malleable iron work, loose, dry, pestled
240 B	351	8.7	6.5	383	Floor sand, same as 240 A, as taken in foundry, molded, tested green, rammed hard
240 C	338	8.7	7.0	356	Floor sand, same as 240 A, as taken in foundry, molded, tested green, rammed light
240 D	338	2*	10.2	244	Floor sand, same as 240 B, air dried

* Indicates estimates or computations from incomplete data.

TABLE XVI. PERMEABILITY TESTS—*Continued*

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
241 A	371	0	1.2	2,074	Floor sand, same foundry as 240, different pile, dry, loose, pestled
241 B	379	7	4.9	510	Floor sand, same as 241 A, molded, rammed hard, tested green
241 C		7	5.5	452	Floor sand, same as 241 A, molded, rammed light, tested green
241 D	344	2*	6.3	392	Floor sand, same as 241 A, molded, rammed hard, air dried before testing
242 A	353	0	1.2	2,051	Floor sand, same foundry as 240 and 241, different pile, loose, dry, pestled
242 B	373	8.1	3.4	734	Floor sand, same as 242 A, molded, rammed hard, tested green
242 C		8.1	7.2	346	Floor sand, same as 242 A, molded, rammed light, tested green
242 D		3*	4.0	624	Floor sand, same as 242 A, molded, rammed hard, air dried before testing
245 A	382	0	19.2	130	Core, made in foundry, using linseed oil as binder, baked in foundry, tested in laboratory, used with sands 240, 241, and 242. One part binder to 43 parts sand
246 B	352	0	28.1	89	Cores 246, 247, and 248 made in same foundry as 243, 244, and 245, using same sand, but resin as binder, in proportions of 1 of binder to 35 of sand
247 B	351	0	29.1	86	
248 B	358	0	26.6	94	
249 C	359	0	22	114	Cores 249 C, 250 C, and 251 C made in same foundry as 243 to 248 inclusive, using a mixed sand made of ½ floor sand and ½ raw core sand, quartz, using resin as binder in proportion of 1 part binder to 35 parts sand
250 C	361	0	21.4	117	
251 C	364	0	20.3	123	
257 A	347	0	1.6	1,550	Floor sand, grey iron foundry, heavy founding, loose, dry, pestled
257 B	360	10	8.7	285	Floor sand, same as A, molded, rammed hard, tested green
257 C	341	10*	13.6	183	Floor sand, same as A, molded, rammed light, tested green
257 D	347	3*	8.0	315	Floor sand, same as B, rammed hard, but air dried before testing
257 E	340	0	6.0	415	Floor sand, same as B, rammed hard, but baked at 400 degrees C. before testing

* Indicates estimates or computations from incomplete data.

TABLE XVI. PERMEABILITY TESTS *Continued*

LABORATORY NUMBER OF SAMPLE	WEIGHT OF TEST CYLINDERS OF SAND IN GRAMS	MOISTURE CONTENT IN PERCENTAGE BY WEIGHT	PERMEABILITY OF CYLINDER IN PERCENTAGE OF STANDARD SAND PERMEABILITY	TIME, IN SECONDS, REQUIRED TO PASS 74 LITERS OF AIR THROUGH TEST CYLINDER	NATURE OF SAND AND CONDITIONS OF TEST
258 A	346	0	1.9	1,332	Floor sand, grey iron work, light founding, same foundry as 257, loose, dry, pestled
258 B	341	9.2	5.6	443	Floor sand, same as A, molded, rammed hard, tested green
258 C	332	9.2	7.8	321	Floor sand, same as A, molded, rammed light, tested green
258 D		3*	6.2	402	Floor sand, same as B, but air dried before testing
259 A	334	0	3.3	768	Facing sand, used with 257 and 258, mixture of 8 parts floor sand, 1 part quartz sand, 1 part loam 256, 1 part sea coal, tested loose, dry, pestled
259 B	357	8.5	4.3	575	Facing sand, same as A, molded, rammed hard, tested green
259 C	322	8.5	14.1	177	Facing sand, same as A, molded, rammed light, tested green
259 D	347	6*	5.5	454	Facing sand, same as B, but air dried before testing
260	380	10	2.8	878	Brass sand, railroad shops, casing heavy locomotive, brass journals, molded, tested green
292	368	8.06	1.8	1,395	Bronze sand, ornamental work, molded, tested green, made by mixing 1 part floor sand 293, 1 part "Red sand" 294, sample as used in foundry
293	392	8.06	2.8	880	Floor sand, same foundry as 292, used as backing sand for bronze work, and for ornamental iron casting, molded, tested green
296 A	418	Not determined	7.9	317	Brass sand, used same foundry as 292, bought in Milwaukee, molded, tested green
296 B	402	Not determined	11.4	218	Brass sand, same as A, but rammed light, tested green
297	303	Not determined	24.5	102	Bronze sand, imported from France, used for facing in bronze, molded, tested green

* Indicates estimates or computations from incomplete data.

TABLE XVI. PERMEABILITY TESTS—*Continued*

Laboratory Number of Sample†	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
500	385	0	19.8	120	Cores 500 to 505 inclusive were made in the Eagle Foundry probably out of sand 5, and represent the type of core material used in grey iron work, in connection with loam 6. No information was obtained as to the kind of binder used or the proportion of binder to sand. Cores 500, 501, and 502 are probably of same sand. Number 503 may have been made of coarser sand than the others.
501	381	0	20.3	123	
502	381	0	20.2	124	
503	341	0	41.6	60	
504			20.3	123	
505	347	0	23.8	105	
506	361	0	16.9	148	Core 506 was made of 1 part of some commercial binder compound to 25 parts of sand (St. Peter) in Crown Iron Works. Cores 507 and 508 were made of the same sand and same binder as 506, but the ratio of binder to sand was 1 to 30.
507	353	0	21.7	115	
508	353	0	21.4	117	
509	382	0	14.9	168	Core 509 used linseed oil as a binder; the ratio of binder to sand being 1 to 45. Cores 510 and 511 were thought to be triplicates of 509, but legend was illegible. Made by the Crown Iron Works, and represent type of core material used in conjunction with loams 255, 256, and 259
510	382	0	15.8	158	
511	383	0	15.8	158	
512	364	0	25.5	98	Cores 512, 513, and 514 were made in the shops of the Soo Line Railroad, representing the type of core material used in brass-founding in conjunction with brass sand 261 (Albany sand). The St. Peter sand 262, was used in making the cores. The nature of the binder used was not stated.
513	366	0	25.5	97	
514	365	0	27.7	90	
515	387	0	20.6	121	Cores 515 to 523 inclusive were made in the foundry of the American Brake Shoe Co., Minneapolis. Cores 515, 516, and 517 are assumed to be triplicates as cores 518, 519, and 520, and cores 521, 522, and 523. They represent the type of core material used in conjunction with loams 271, 272, 273, and 266, 269, and 270. The sand used was presumably St. Peter, but the binder in each sample is not known.
516	381	0	25	100	
517	384	0	23.1	108	
518	381	0	21.9	114	
519	382	0	22.7	110	
520	383	0	21.2	118	
521	364	0	17.5	143	
522	370	0	16.0	150	
523	363	0	16.1	155	

† Samples 500 to 523 inclusive are cores made in different foundries in Minneapolis and St. Paul, in the standard core box furnished by the survey, with the core sand used in their regular foundry work, and such binders as they used in their foundry work, such as resin, linseed oil, flour, molasses, etc. Cores 515 to 523 inclusive were made using sand 277 and were made in the same foundry.

RESULTS OF PERMEABILITY TESTS

Permeability tests are recorded in Table XVI, and include tests of clean quartz sand of mixed sizes as obtained from the pits; the same quartz sand sized by the screen sieves to 20, 40, 60, 80, 100, and 200 mesh; loams in the dry state and in the molded state; brass sands, dry and molded; core sands, dry and with artificial bond; and various mixtures of sands, loams, and other materials employed in the foundries.

The permeability of the material is expressed in Table XVI in two ways (a) in the actual time in seconds required to pass 74 liters of air through the column of sand 2 13/32 inches in diameter and 3 inches long, at constant pressure (see page 43), and (b) in percentage permeability in which a standard sand is taken as 100 per cent permeable.

A few experimental tests were run on the permeability of carefully sized sands to test the apparatus and find whether the results agreed with those obtained by other workers with similar material, and to find to what extent the permeability test could be relied on as reflecting the structure in molding sands in general.

Permeability of sized sands.—Samples 228 A, B, C, D, E, and F were sized sands obtained by screening sand from the St. Peter and Jordan formations to the sizes shown in the table. The coarse sizes, A, B, and C, came principally from the Jordan formation, and the finer sizes, D, E, and F, came principally from the St. Peter formation. The nature of the material and the character of the grains were essentially the same in each case, that is, the sand was essentially pure quartz, the larger grains of which were exceptionally well rounded, and the smaller sizes less so.

It will be observed that the 20- to 30-mesh sand, 228 A, was 100 per cent permeable, agreeing with standard sand 215, and that the other samples, B, C, D, E, and F, showed a gradual decrease in the permeability consistent with the increase in fineness.

Samples 200 A, B, C, and D represent a second series of sized sands obtained by sizing quartzite screenings, resulting from crushing Sioux quartzite. The results of this tests were not entirely consistent, since the 20- to 40-mesh sand showed less permeability than the 40- to 60-mesh sand. Similar discordant results were observed by King,[16] in testing the permeability of crushed glass, sized to 20, 40, 60, and 80 mesh.

The series of samples 223-224, A, B, C, D, and E, represent an experiment with a series of mixtures of two loams, differing noticeably in permeability, to see in what degree the permeability of the different mixtures would reflect the proportion of the two loams present.

These loams were given 10 per cent of water after mixing and were rammed into molds in the usual way. They were tested green, except in the case of E, which was tested loose dry. This series is of interest in that the mixture of 60 per cent of 223 and 40 per cent of 224 showed the maximum permeability of green sands, which was noticeably greater than the permeability of either of the constituents of the mixture.

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[16] *Op. cit.*

Many samples were tested both as loose dry sand, pestled to break them up into individual grains, and also as damp molded sand. The molded sand was in some cases tested both as green, damp sand and as air-dried after molding. In general the molded sand, even when rammed harder than ordinarily, was more permeable than the loose dry sand. Most of these sands were loams in the proper sense of the term since they carried a considerable clay content, but they were sands in the sense foundries use that term. With some materials, however, different results were obtained, that is, the loose dry sand was more permeable than the damp molded sand, as for example in sample 9.

The difference in permeability of the sands in the loose dry condition and in the damp molded condition was plainly due to granulation. Some sands, when moistened with water, allowed to stand, and then riddled, granulated readily, developing clusters of grains of considerable size, and the granules were sufficiently coherent to stand up against ramming in the mold; so that after molding intergranular spaces remained large enough to make the mass more than ordinarily permeable. Other sands treated in the same manner did not granulate as in the case of sand 9; the subsequent molding served only to make them more compact than when dry, and the permeability was correspondingly less.

From the mechanical analyses, Table X, it will be observed that sand 9 is moderately coarse. The percentage of fines, including the silts, is small, and the clay content, 2 per cent, is sufficient for bonding purposes. Sands of that physical constitution do not develop granules that withstand ramming in the mold.

Examples of sands that granulated readily, gave conspicuously permeable masses when molded, and were rather dense, or but slightly permeable when dry, are seen in samples 208, 240, 241, 242, 257, and 259. Comparing the mechanical analyses of these sands, Table XI and XII, it will be seen that they show a rather wide range in constitution. If the fines alone are considered, it will be seen that the 30-minute and 15-minute silts and the sand passing the 200-mesh screen make 81, 27, 22, 26, 33, and 25 per cent respectively of the several samples. Sand 208, which shows an exceptionally large proportion of fines, is essentially a brass-molding sand, though not in general use, whereas the other samples referred to, ranging as low as 22 per cent of fines, are loams.

In Table XVI samples of 240 to 251, inclusive, come from the same foundry, and represent both the molding sands and the core sands used.

Samples 245 to 251, inclusive, were cores made in the foundry by skilled molders, using their own core sand, their own binders, and baking the cores in the foundry ovens, so that these cores were comparable in every way with their regular practice. The remarkable uniformity in the permeability of the cores made in triplicate illustrates the degree of skill attained by careful molders.

Samples 240, 241, and 242, representing the molding sand in this foundry, are ordinary loams, as will be seen from the mechanical analyses, Table XII. They carry 2.5 to 4 per cent of clay, and the usual percentage of fine and coarse sizes. The work in this foundry was in malleable iron, mostly small castings, where the soundness of casting and smooth surface finish were important.

This series of samples illustrates a close approach to the proper permeability for sands for light work in iron. It will be observed that the permeability in the green molds ranged from 3.4 to 6.4 per cent where hard rammed, and 4 to 10.2 per cent in air-dried molds. In Table XV it will be observed that this same series of sands, 240, 241, and 242, showed good tensile strength both in green and in dry briquets.

Samples 257, 258, and 259 represent another series of sands or loams in use for heavy work in grey iron. In this foundry a facing sand, 259, was used, and the molds were dried in all cases before casting. Number 259 D is the most significant test of this series and shows a permeability of 5 per cent. The sand used in this foundry back of the facing sand 259 was still more permeable and was used in the molds for heavy work. This sand, 259 D, as will be seen from Table XV, had a tensile strength, air-dried, of 17 pounds, and this was still further increased in actual foundry practice by spraying the inner surface of the mold, after completion, with molasses water and drying the surface by the aid of a torch. In this manner sand 259 was made to stand up, and give a good skin, or surface finish, to castings weighing several tons. Samples 506 to 511, inclusive, represent the type of core sand used in this foundry, in connection with the molding loams, 257, 258, and 259.

Sample 260 illustrates the permeability required for brass sand for heavy work, viz., 2.8 per cent. This sand was used in railroad shops for casting brass journals weighing 220 pounds for locomotives and gave exceptionally good results. Soundness of the casting was the essential feature in this work. It will be noted that the permeability is much less than for iron work. Samples 512, 513, and 514 are cores made from the core sand used in this railroad shop in connection with the brass sand, 261, the permeability of the cores being 25 to 27 per cent.

Sample 292, which was used for ornamental bronze work, shows only 1.8 per cent permeability, but the castings here were for the most part light and a backing sand having a greater permeability was generally used.

Samples 500 to 505 were cores made in a foundry doing grey iron work, mostly light castings. No information was furnished by the foundry as to the nature of the bond used, the proportion of the bond to the sand, or whether the six samples were all the same or represented different mixtures. The results of the test indicate that sample 503 was a different mixture from the others.

Samples 506 to 511 represent a set of cores made by a foundry doing heavy founding in grey iron. Samples 507 and 508 were made. using a commercial binder with 1 part of binder to 30 parts of sand. Sample 509 used 1 part linseed oil to 45 parts of sand. Cores 510 and 511 were probably triplicates of 509.

Samples 515 to 523, inclusive, represent three series of triplicate cores, 515, 516, and 517 being one triplicate set; 518, 519, and 520 being a second set; and 521, 522, and 523 being the third set. No information was furnished by the foundry as to the kind of bond used. or the proportion of the bond to the sand, except that the cores represented their regular foundry practice. The foundry was working in grey iron, mostly light casting.

POROSITY TESTS

In setting up Table XVI figures on porosity were omitted, but upon further consideration it seemed advisable to give them, and they are shown in Table XVII.

The porosity percentages here given are of unequal value or accuracy by reason of the factors involved in some of the computations. With the samples of loose, dry sand the porosity was actually determined by the method described on page 41. For the neutral sands and loams the porosity percentages are dependable, but in the samples of floor sand or other used sand more or less foreign material was present such as chopped straw, sawdust, coal, etc., the specific gravity of which might be 1 or less than 1, or in any event less than the assumed specific gravity of 2.7. Again the used sands may or may not have contained particles of metal —brass, iron, etc., the specific gravity of which might be 5 or more; thus introducing into the computations factors, the value of which was unknown. Different cylinders were used for weighing materials for permeability and for porosity tests and the results of packing were not identical.

The porosity of the molded cores was determined by taking the actual weight of the core, which was of the same volume as the cup *V*, Fig. 6, and computing the porosity after the method described on page 41. For cores that contained only natural sand or loam, and were air-dried, the

TABLE XVII

Laboratory Number of Sample	Approximate Porosity in Percentage by Volume	Laboratory Number of Sample	Approximate Porosity in Percentage by Volume	Laboratory Number of Sample	Approximate Porosity in Percentage by Volume
215 stand-		223-224 D	37.8*	258 C	50.8
ard sand	33.5	223-224 E	43.7*	258 D	
1	35.3	225	38.6	259 A	45.7
2 X	40	226	37	259 B	46.5
2 Y	39.4	227		259 C	50.9
2 Z	39*	228 A	35.4	259 D	46.5*
3 J	47*	228 B	35.7	260	43.7
B 4	42	228 C	36.2	292	44.0
C 4	42	228 D	37.5	293	41.1
9 A	37	228 E	38.0	297	
19	33.6	228 F	39.8	500	37.4
21	33.6*	240 A	41.8	501	38.0
200 A	49.4	240 B	46.3*	502	38.0
200 B	50.4	240 C	47	503	44.5
200 C	48.5	240 D	46	505	43.5
200 D	48	241 A	39.7	506	41.3
208 A	47	241 B	42.9	507	42.6
208 B	39	241 D	44	508	42.6
208 C	44	242 A	42.6	509	37.9
215	33.5	242 B	44.2*	510	37.9
220	35.4	245 A	37.8	511	37.7
221 A	34	246 B	42.4	512	40.8
221 C	35.9	247 B	42.6	513	41.1
222 B	34.9	248 B	43.4	514	40.6
222 C	39*	249 C	43.4	515	37.0
223 A		250 C	41.3	516	38.0
223 B	33.6	251 C	40.8	517	37.5
224 A	41.4	257 A	43.5	518	37.0
224 B		257 B	47.3	519	37.9
224 C	45.6*	257 C	49.5*	520	37.7
224 D		257 D	47.3*	521	40.8
223-224 A	42.2*	257 E	44.7	522	39.8
223-224 B		258 A	43.7	523	40.9
223-224 C	35.4*	258 B	49.4		

* Indicates estimates or computations from incomplete data.

porosity may be accepted as accurate, whereas for cores made of used sand the factor of variable specific gravity above mentioned may be involved and might affect the computation.

Again in computing the porosity of the damp, "green" molded cores the water content was deducted from the weight of the core on the assumption that the water was absorbed by the clay and did not affect the porosity, which assumption might be open to question.

It will be observed that the porosity of the standard sand used, viz., No. 215, is 33.5 per cent, and that practically all of the other samples run higher than that figure. The porosity of the air-dried cores also runs high, which is again consistent since they represent a structure in the mass abnormally open by reason of granulation. It is improbable that the variations in specific gravity above suggested appreciably affected the porosity computations, but this possibility must be taken into account.

As stated elsewhere, the percentage porosity is no measure, and not necessarily an index of the permeability; in fact, in a series of sands ranging from very coarse to very fine, and otherwise the same in constitution, the permeability would necessarily be in reverse ratio to the percentage porosity, which is illustrated by the fact that standard sand 33.5 per cent porous is 100 per cent permeable, whereas clay or heavy loam is 50 per cent or more porous, and practically impermeable.

CONCLUSIONS

From Table XVI it will be seen that there was a wide range in the permeability of the molding sands in actual practice. There is no very evident relation between the kind of founding done and the permeability of the mold. In foundries where the greatest care and most attention were given to the sand, the permeability of the mold ranged from 4.5 to 7 per cent, and these limits may be taken as normal for iron foundings. In brass founding the permeability of the mold may be taken as 1.5 to 3 per cent.

The permeability of cores may be taken as ranging from 15 to 30 per cent with little or no relation to the kind of work done, as evidenced from Table XVI. An exhaustive study of the problem would no doubt show a percentage permeability of the core varying with the nature of the founding done.

The material preferred for core work is a quartz sand with the least possible amount of silts, and with little or no clay, since organic bonds that will burn out in the founding process, leaving the sand loose or incoherent, are essential in most work. The St. Peter sandstone affords an abundance of this type of sand well suited to ordinary founding. Examples of this sand are samples 1, 5, 21, 28, 31, 64, 90, 145, 262, and 299, all in Table IX.

Coarser quartz sand, sometimes desired for cores in heavy work in grey iron and for founding in steel, may be readily obtained from the Jordan formation, examples of which are samples 8, 19, 159, 166, 167, 170, 173, and 175, Table X.

The permeability tests of the molding sands, some of which are given in Table XVI, brought out many interesting facts in connection with the permeability of the same materials under different treatments, and the relative permeability of different materials under like treatment. For example, with the same loam or sand dampened and molded, some loams showed greater permeability in the green or damp condition than in the air-dried condition, whereas with other loams the reverse was true. Again some sands or loamy sands showed greater permeability in the loose dry state than in the damp molded state, whereas other sand showed the reverse. Such seemingly erratic behavior was evidently due to peculiarities in the physical constitution of the particular materials by virtue of which some readily took on a granular structure, whereas others did not, under the same treatment.

Tests of the cores made in different foundries indicated that the personal equation of the molder was an apparent factor in the permeability. Several cores made by the same molder, from the same sand at the same time under supposedly uniform conditions showed wide variations in the permeability of individual cores, whereas other groups of cores made by other molders in other foundries from similar materials showed remarkably uniform permeability. It is of course possible that some peculiarity in the foundry practice might account for these differences in part, and the personal equation of the molder may not have been wholly responsible. However, on the whole, the skill of the molder seemed in some instances to be the chief factor.

In sands where no artificial bond was used, and dependence was placed on the clay or other material inherent in the natural sand, variations were observed in the permeability which were not directly related to the percentage of clay present; indicating that the nature of the clay itself was a factor in permeability.

The percentage of silts in the sand affected the permeability of the sample differently in different types of sand, and also gave different results with the same sand in the various foundries. In the latter case the results would seem to be due to the foundry practice in handling the sand; but in the former, the difference in the behavior of the silts appeared to be due to some peculiarity inherent in the sand or the silts. Some sands, if properly handled, get rid of the silts by granulation, in which case the silts adhere to the larger grain, or the silts themselves gather into granules, giving an open permeable sand; whereas in other sands, no matter how handled, the silts remain as independent silty material that clogs the interstitial spaces, decreasing permeability.

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The University of Minnesota

MINNESOTA GEOLOGICAL SURVEY

WILLIAM H. EMMONS, DIRECTOR

BULLETIN NO. 19

CONTRIBUTIONS TO THE GEOLOGY OF THE MESABI RANGE

WITH SPECIAL REFERENCE TO THE MAGNETITES OF THE IRON-BEARING FORMATION WEST OF MESABA

BY

JOHN W. GRUNER

MINNEAPOLIS
The University of Minnesota
1924

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THE GEOLOGY OF THE MESABI RANGE

CHAPTER I

INTRODUCTION

This paper treats the geology of that portion of the Mesabi Range that lies west of the town of Mesaba (Fig. 1). The Mesabi Range east of Mesaba was recently surveyed by Grout and Broderick,[1] and the Gunflint Range by Broderick.[2]

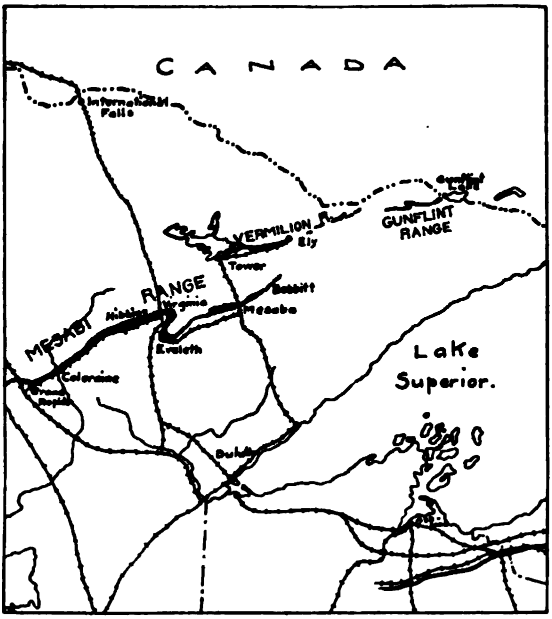

FIGURE I. SKETCH MAP SHOWING THE LOCATION OF THE MESABI AND GUNFLINT RANGES

The subjects treated include (1) the stratigraphic subdivisions and structure of the iron formation, (2) the occurrence of large magnetite bodies, possibly ore reserves for the future, (3) the origin of the formation and of the ores. The geologic setting of the district as a whole is briefly reviewed.

---

[1] Grout, F. F., and Broderick, T. M., The magnetite deposits of the eastern Mesabi Range, Minnesota: Minn. Geol. Survey Bull. 17, 1919.

[2] Broderick, T. M., Economic geology and stratigraphy of the Gunflint iron district, Minnesota: Econ. Geol., vol. 15, 1920, pp. 422-50.

FIELD WORK AND ACKNOWLEDGMENTS

The writer's work in the district was begun in the summer of 1919, with Dr. T. M. Broderick in charge. It was continued by the writer with the assistance of Mr. S. C. Lin, and Mr. H. A. Schmitt, in the summers of 1920 and 1921.

In gathering the data all of the mining companies of the range co-operated heartily. Special thanks are due to Mr. W. J. Olcott, president, and Mr. J. Uno Sebenius, general mining engineer, of the Oliver Iron Mining Company, who gave permission to examine all their drill cores and maps used in the construction of the plates accompanying this report; also to the E. J. Longyear Company. In the laboratory work and in writing this paper, numerous suggestions and invaluable assistance were received from Dr. W. H. Emmons and Dr. F. F. Grout.

PREVIOUS GEOLOGIC WORK

On account of the scarcity of outcrops of the iron-bearing formation on the West Mesabi Range, it was not till 1891 that the productive part of the range was discovered. The East Mesabi Range had attracted explorers and was described as early as 1866.[3] Later this region was described again by Chester.[4] The leanness of the hard iron-bearing formation (taconite), made development impossible at that time.

When the richer hematites west of Mesaba were discovered the rush of 1891 and 1892 began. N. H. Winchell, H. V. Winchell, and J. E. Spurr[5] have described the geology of the district. Leith[6] published a monograph of the district in 1903, giving a summary of the history of the district. In 1912 a monograph describing the whole Lake Superior region was published by Van Hise and Leith[7]. The genesis of the iron-bearing formations is treated at length. A number of papers and reports have been published since 1912. Those by Wolff[8] are of special interest because they give a classification of the iron-bearing formation into subdivisions. Grout and Broderick[9] carried the subdivisions still farther on the East Mesabi Range and found several good horizon markers. Lately a new mining camp has sprung up at Babbitt on the East Mesabi Range, where the Mesabi Iron Company is actively engaged in extracting magnetite from the richer beds of the taconite.

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CHAPTER II

GENERAL GEOLOGY

STRATIGRAPHY

All the rocks of the Mesabi district have been described in great detail by the Minnesota and the United States Geological Surveys. The present study is confined to the iron-bearing formation. A short review of the stratigraphy is given below.

Quaternary system	
Pleistocene series	Glacial drift
Unconformity	
Cretaceous system	Conglomerates and shales
Unconformity	
Algonkian system	
Keweenawan series	Duluth gabbro and associated diabase sills and dikes
Unconformity	
Huronian series	
Upper Huronian (Animikie group)	Virginia slate Biwabik formation (iron-bearing) Pokegama quartzite
Unconformity	
Lower-Middle Huronian	Giants Range granite Slate-graywacke, conglomerate formation
Unconformity	
Archean system	Greenstones and schists

ARCHEAN SYSTEM

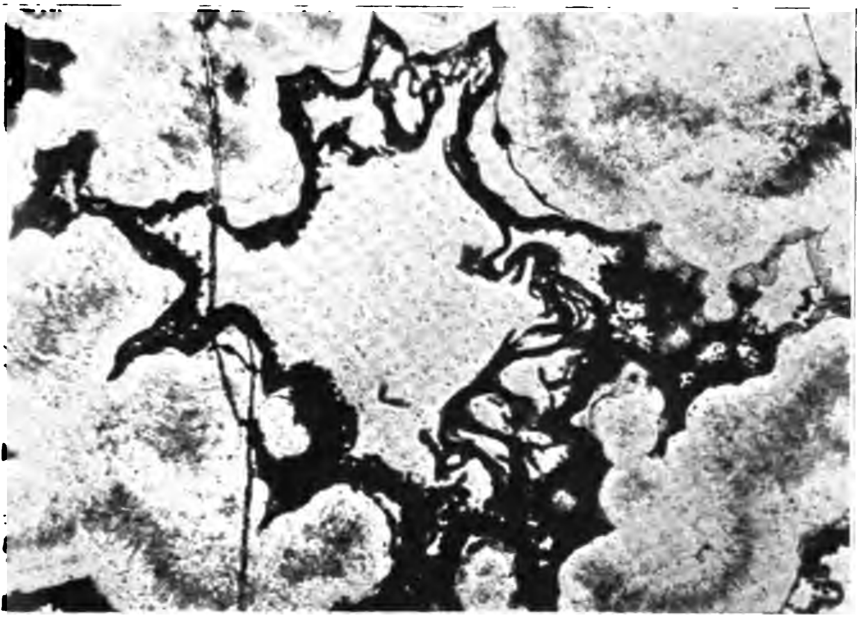
Greenstones and Schists

The greenstones are mostly green to gray schists, and represent much altered basic igneous rocks and, to a minor extent, sediments. Where foliation of the rocks is pronounced the name schist is preferable to greenstone. The greenstones occupy relatively small areas north of the iron-bearing formation between Mountain Iron and the Spring Mine in R. 14 W. They are not directly in contact with the Biwabik formation, but are separated from it by the Pokegama quartzite and commonly also by Lower-Middle Huronian graywacke and schist.

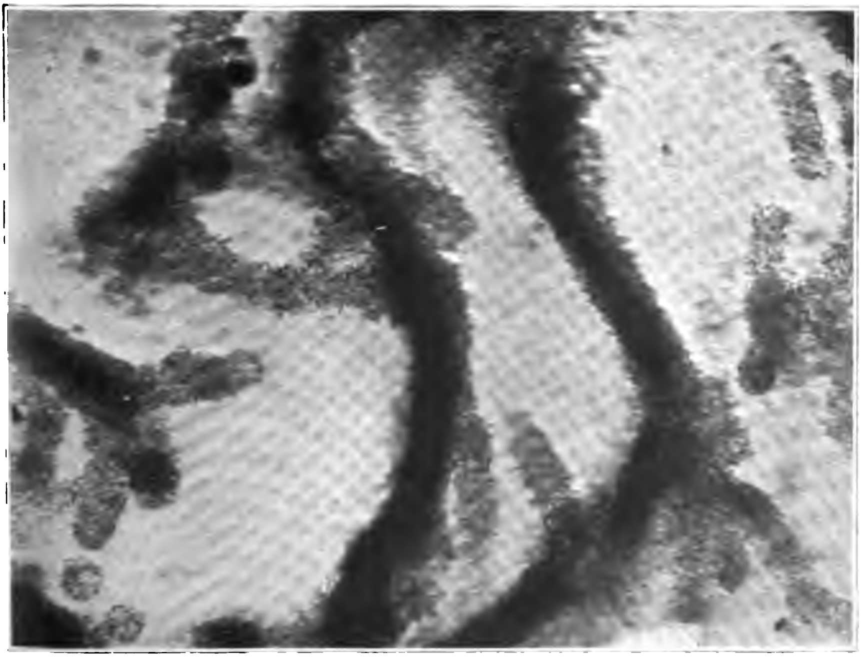
ALGONKIAN SYSTEM

Lower-Middle Huronian Series

Graywackes and slates.—To the casual observer the graywackes and slates look somewhat like the Archean greenstones and schists, but their sedimentary character is shown by bedding planes in many places. Slaty



A. MICRO-ORGANIC STRUCTURES (ALGAE?) IN CHERT PEBBLES. THE CHERT SHOWS LARGE COLLOFORM OUTLINES. THE BROWNISH GREEN ORGANISMS (BLACK IN PICTURE) OCCUR ALONG THE OUTSIDE OF THE "SCALLOPS" IN A MATRIX OF THE SAME KIND OF CHERT. ORDINARY LIGHT. x 88. SLIDE M 904 a



B. A PART OF STRUCTURES IN A, HIGHLY MAGNIFIED. THE DARK MATERIAL IS OF A GREENISH COLOR (PROBABLY A FERROUS IRON SUBSTANCE) AND CONSISTS OF MINUTE RODS OF UNIFORM SHAPE AND SIZE. x 660. SLIDE M 904 a

cleavage is common. The graywackes and slates are found in the area north of the Pokegama quartzite between Biwabik and Virginia. They are not in direct contact with the iron-bearing formation. Pokegama quartzite separates the two.

Giants Range granite.—Granite intrudes the greenstone, the graywacke, and the slate and forms most of the hills which make up the Giants Range. East of Mountain Iron the granite is hornblendic; west of Mountain Iron biotite predominates. The granite is coarse except near intrusive contacts. Pegmatite dikes are very common in it.

Upper Huronian Series (*Animikie Group*)

Pokegama quartzite and conglomerate.—The Upper Huronian sediments lie on the truncated edges of the Lower-Middle Huronian graywackes and slates. The Pokegama quartzite consists of a conglomerate as its base and a micaceous gray, green, or pink quartzite above the conglomerate. Pokegama quartzite, though very thin in places, underlies the Biwabik formation practically everywhere.

The conglomerate at the base of the quartzite was studied in a number of places where it is in contact with the older rocks. It is persistent though thin (a few inches to 6 feet). Its pebbles consist chiefly of graywacke, slate, greenstone, quartz, granite, and chert. Usually pebbles of the rock immediately underlying the conglomerate predominate. In size the pebbles vary from a fraction of an inch to one foot in diameter. The matrix may be quartzite or may consist of soft chloritic material where weathered.

A special study was made of patches of conglomerate in the SW¼ sec. 29, T. 58 N., R. 18 W., about half a mile northeast of Eveleth, in the NW¼ sec. 34, T. 59 N., R. 18 W., about one mile north of Mountain Iron, and in the SE¼ sec. 26, T. 58 N., R. 18 W., about two and a half miles northwest of North Hibbing. In these places the conglomerate was deposited on a rather uneven and broken erosion surface, and also fills fissures and cracks in the older rocks. Most of its pebbles are graywacke and slate of flat shapes. Quartz and chert pebbles which are present are usually fairly well rounded. The matrix consists of crystalline material resembling chloritic schist. Often the pebbles are so numerous and so close together that there is little room for matrix.

Cutting through the conglomerate and extending into the older underlying rocks are small veins and irregular areas of chert. The occurrence of this chert in the older rocks was described by the writer in 1922,[1] and is discussed later in this report. At that time it was not known that this chert also penetrates the conglomerate at the base of the Pokegama quartzite. The chert is green, light gray, dark gray, or reddish in color and in places shows peculiar markings as small rings or spots the size of greenalite granules. It may be much decomposed and looks "worm-eaten." Pyrite in minute cubes is common in it. The chert is indistinguishable either in the hand specimen or under the microscope from any other cherts of the Lake Superior region. This chert contains fossil micro-organisms. As noted, the conglomerate at the base of the Pokegama quartzite contains well-rounded chert pebbles. The chert of these pebbles resembles the "vein" chert just described. It is possible, but hardly probable, that the chert was formed in the same body of water in which the conglomerate was laid down, that the chert was broken up immediately and pieces of it carried into the conglomerate then forming. Organic structures have been found in two pebbles from sec. 26, T. 58 N., R. 21 W., about two miles northwest of Hibbing. Plates III and IV are photographs of these fossils. Somewhat similar structures have been found in other pebbles of the conglomerate north of Mountain Iron and northeast of Eveleth. (See Pl. V.)

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[1] Gruner, J. W., The origin of sedimentary iron formations; the Biwabik formation of the Mesabi Range: Econ. Geol., vol. 17, 1922, p. 417.

Overlying the conglomerate there is a varying thickness (a few feet to 200 feet) of quartzite most of which is micaceous. Only toward the top of the formation does it become a coarse-grained massive quartzite.

Biwabik iron-bearing formation.—Overlying the quartzite practically conformably is found the Biwabik iron-bearing formation, about 400 to 750 feet thick. Its detailed description is presented in Chapter III.

Virginia slate.—The Virginia slate overlies the Biwabik formation conformably on the south side of the range. The two formations are separated by a persistent layer of impure crystalline limestone with an average thickness of about 10 feet. Drill cores in places show traces of a limestone conglomerate at the contact of the limestone with the Virginia slate. The slate is usually gray and varies in hardness. Much of the rock easily splits along the bedding planes but some breaks with difficulty and shows conchoidal fracture. The total thickness of the slate is probably several thousand feet. From a deep drill hole we know that it is at least 1900 feet thick in the central part of the range. In the examination of many thousands of feet of drill cores of Virginia slate no indication was found that deposition of iron-bearing formation, even on a very small scale, took place after the slate had begun to form.[2] Very small lenses of light gray chert, however, are found occasionally in the slate.

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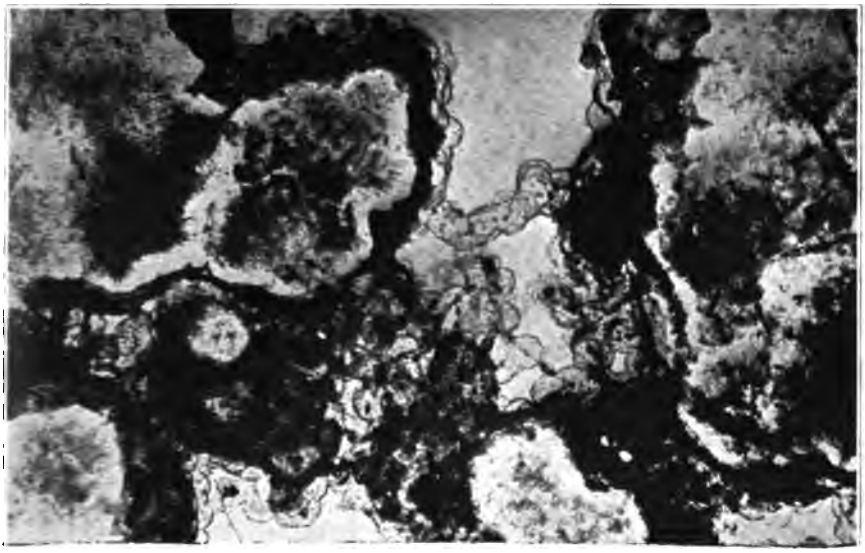
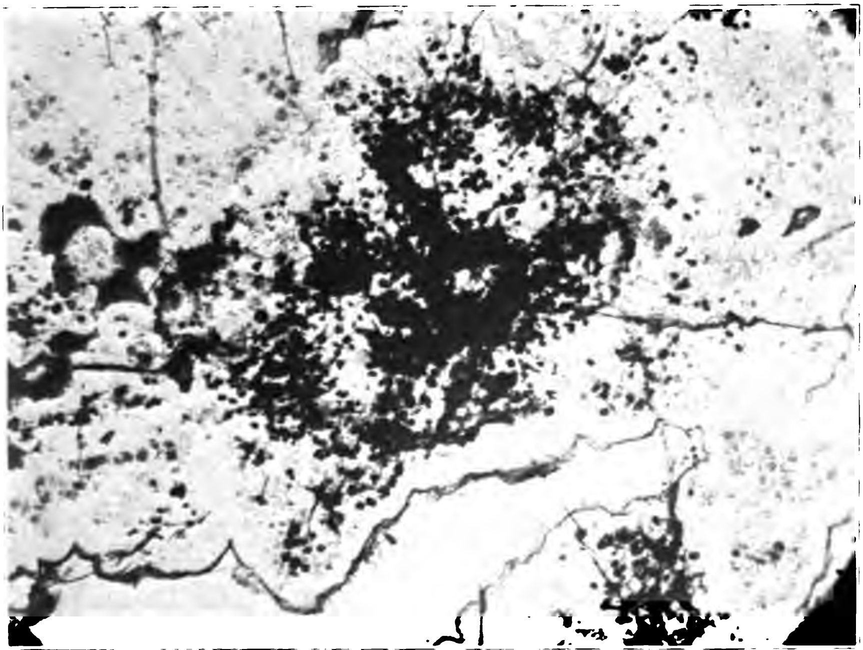
[2] In sec. 12, T. 56 N., R. 23 W. (Pl. II) some greenalite is interstratified with slate, but on account of the predominance of the slate this portion is included in the Virginia slate.



A. PECULIAR CHAINS OF MINUTE CONCENTRIC STRUCTURES IN CHERT PEBBLES. THE BLACK IN THE PICTURE CONSISTS OF IRON AND GREENISH MATERIAL WHICH RESEMBLES ALTERATION PRODUCTS (AMPHIBOLE-LIKE) OF GREENALITE. ORDINARY LIGHT. x 88. SLIDE M 904 d



B. "COLONIES" OF MINUTE, ROUND GRAINS IN THE CHERT PEBBLE WHICH CONTAIN THE ORGANISMS OF PLATES III A AND B, AND PLATE IV A. THESE GRAINS CONSIST OF BROWNISH MATERIAL AND STRONGLY SUGGEST ORGANIC ORIGIN IN THEIR ARRANGEMENT. x 77. SLIDE M 904 x

Keweenawan Series

The encroachment of the Duluth gabbro and the intrusion of sills of basic rock in the iron-bearing formation east of Mesaba are well known. During recent years drilling and underground mining have disclosed a number of intrusive dioritic masses near Aurora and dikes of highly altered igneous rocks in the Miller, Mohawk, Belgrade, and "Corsica-80" mines. There are indications that intrusions occur as far west as Virginia. (See p. 27.)

Diabase dikes and gabbro in larger masses occur north of the Biwabik formation, intrusive into the Giants Range granite as far west as Nashwauk.[8]

CRETACEOUS SYSTEM

Conglomerates and shales overlie a number of ore bodies west of Eveleth. Cretaceous fossils have been found in the shales west of Hibbing, but east of this town the age of the conglomerates can only be inferred from their similarity with those west of Hibbing.

QUATERNARY SYSTEM

Pleistocene Series

On the Mesabi Range, from Mesaba westward, probably not more than half a dozen exposures of the Biwabik formation can be found. In all other places a mantle of glacial drift, ranging from one to three hundred feet thick, or more, conceals the formation. The drift is thickest at the western end and thinnest at Mesaba, east of which outcrops of the iron-bearing formation are very numerous.

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[8] Observed by G. A. Thiel, I. S. Allison, and the writer.

CHAPTER III

DETAILED DESCRIPTION OF THE IRON-BEARING FORMATION

MINERALS OF THE IRON-BEARING FORMATION

The minerals noted in the following paragraphs are those easily observed in the hand specimens.

Greenalite and *amphiboles,* ferrous silicates with some magnesium, are found in many beds of the iron formation, as dull green or grayish green granules that rarely exceed one and one-half millimeter in diameter. The green microscopic needles of amphibole silicates which occur as metamorphic products of greenalite, retaining its granule shape, are included in the term greenalite as used here. The granules as a rule are embedded in a matrix of chert or dark slaty material. In the overlying Virginia slate greenalite is absent. It is the opinion of many geologists that by far the largest portion of the iron oxides and cherts is derived from this mineral in the processes of alteration and decomposition.

Chert is by far the most abundant mineral in the iron formation. It is usually white or light gray. When it has the characteristic greenalite structure it may be greenish gray. Most of the chert has been recrystallized and it is now a very fine aggregate of quartz crystals. Chert resembling flint in appearance occurs as very small lenses in the slaty phases of the iron formation. Coarsely crystallized quartz is common as filling in fissures and joints.

Magnetite was recognized for many years in the Biwabik formation, but its abundance has only recently attracted attention. In very small amounts it may be seen with the aid of the microscope in almost any fresh phase of the formation. It is present in amounts sufficiently large to attract an ordinary horseshoe magnet either as granules the size of those of greenalite with chert as matrix, or as dense fine-grained bands between cherty or slaty material. Its dark gray or black color and metallic luster, as a rule, are conspicuous. There are also mixtures of hematite and magnetite that look reddish brown or purple and attract the magnet. The eye alone cannot be relied upon in identifying the magnetite. Other less common phases of the occurrence of this mineral will be described later.

Hematite and *limonite* are very abundant in the iron formation. They are commonly mixed. In the following pages such mixtures are sometimes referred to as "ferric oxides" or "oxidized material." These oxides are recognized by their conspicuous purple, red, brown, and yellow colors. Black oxides are not all magnetite; some are hematite. Much of the hematite is derived from magnetite and its texture and distribution are much the same.

Carbonates of various composition are common in many beds that have not been decomposed. The abundance of carbonates has probably not been sufficiently emphasized heretofore. They occur especially with greenalite and slaty material, but are also common in the cherty beds. They occur as patches or bands, and also as individual crystals scattered through the rock. The sparkling of cleavage faces generally makes their recognition possible. In exceptional cases large crystals or aggregates may be noted. In color the carbonates range from white to brown and grayish, and their composition probably varies accordingly, though most of them are brownish yellow and appear to be siderite. An exception to this is the limy carbonate which is found at the top of the iron formation. This resembles a white, fine-grained, recrystallized limestone in every respect.

Kaolinite is present in the decomposed slate, the so-called paint rock. It is mixed with oxides of iron and therefore is usually some shade of red.

Graphite has been seen as very thin grayish black seams or films. The seams are often irregular and jagged in cross section, and are typical stylolites. (See Fig. 2.) At some places they form the dividing line between greenalite and slaty material or carbonates.

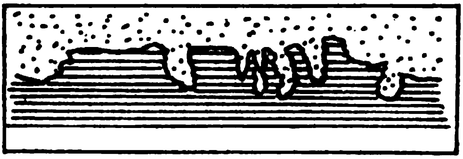


FIGURE 2. STYLOLITIC SURFACE BETWEEN CARBONATE AND SLATE IN THE BIWABIK FORMATION, NATURAL SIZE

Pyrite in very small quantities is widely distributed in the iron formation, especially in the greenalite and slate. It everywhere occurs as a replacement. A few large cubes were found in cherty taconite.

Marcasite was observed in fissures in ore bodies as a very late mineral.

Chalcopyrite has been noted in and near minute quartz veinlets in drill cores.

Manganese oxides and *hydroxides,* as black coating and probable replacement of iron oxides, are found locally in some ore bodies, especially near or in quartz veins.

Minerals in the slate must be treated as a whole, for individually they are indistinguishable as such to the naked eye. They are very fine grained and their aggregates are dull green, gray, brown, or black. All minerals that were mentioned in the preceding paragraphs are present in the slate. Amphiboles, chlorites, and carbonaceous material also occur in the slates.

ROCKS OF THE IRON-BEARING FORMATION

Taconite is a term which locally is applied to nearly any phase of the Biwabik formation. No better term has been suggested for a rock which has the characteristic granule texture and consists chiefly of chert and iron oxides. Ferruginous chert is another name used for the main phase of taconite. According to the phase of the formation the term taconite may be modified by a word expressing the physical properties or chemical composition. Slate is another convenient term for certain beds and in this report refers to a dense, very fine-grained rock which usually shows distinct banding. True slate, that is, a rock with slaty cleavage due to metamorphism, does not occur in the Biwabik formation. Paint rock is a local term that is used for the red-banded decomposed slate.

In the following paragraphs various kinds of taconite and slate will be described. The classification is based on the physical properties and the composition of the rocks as they may be seen without the aid of the microscope. An ordinary horseshoe magnet was used to detect magnetism and its intensity. Drill cores furnished most of the information regarding the magnetic taconite. Detailed descriptions, necessary for the interpretation of the maps and sections, are given below.

GREENALITE AND GREENALITE SLATE

Greenalite and greenalite slate have been described by Winchell, Spurr, Leith, and others, in papers already mentioned. Greenalite commonly is closely associated with the slaty beds of the Biwabik formation. The layers of greenalite are usually thin—rarely a few inches thick. Siderite is often associated with these layers, especially on the western half of the range.

The greenalite and greenalite slate as a whole are dark grayish green and are considerably softer than the greenalite taconite mentioned later on page 12. The greenalite granules are usually a little lighter in color than the groundmass. They are soft and in the polished specimens appear somewhat duller than the matrix. They may be very abundant with little groundmass, or very scattered in a large field of groundmass. Few have a greater diameter than one millimeter. The larger ones resemble small pebbles in some specimens. When the matrix is siliceous and the greenalite granules are partly replaced by chert and iron oxide, the rock is a transition to greenalite taconite and cherty taconite. On the other hand, where granules of greenalite are few there is a gradation into slate.

Weathered phases of greenalite and greenalite slate have not been distinguished from those of greenalite taconite with certainty, but it has been observed that the layers next below the layer known as Intermediate Slate which usually are greenalite when unaltered, form yellow limonitic ore on decomposition.

SLATE

The term slate has been used to describe dense, banded rocks in which the grains are of microscopic size. Slaty cleavage is not developed, but the banding and ease of splitting parallel to the bedding planes is pronounced. It may be brought out by color contrasts, or by layers of somewhat coarser grained material interstratified with the very fine-grained. Unless specified otherwise, the slate contains no considerable portions of magnetite or other minerals that could be easily identified in the hand specimen. It generally is dark green, gray, or black, breaks parallel to the bedding, or with conchoidal fracture across it. Its hardness varies with its composition. Very siliceous hard slate is almost as common as softer slate consisting mostly of iron and aluminum silicates. Carbonates are important constituents of the slate. Slaty varieties of taconite are common in any horizon of the Biwabik formation, but slate as defined here is found only in the Lower Slaty and Upper Slaty divisions. In the former it is best developed in the so-called "Intermediate Slate" which forms the bottom beds of the Lower Slaty division. It is dark gray to black in color and is always softer than the other phases of the undecomposed formation. It presents a uniform appearance, and contains much less greenalite than in any other slate beds.

The decomposition of the slates results in the formation of kaolin, hematite, and limonite. The slate first becomes lighter colored and crumbles easily. Where decomposition is far advanced there develop the well-known paint rock layers of which the altered Intermediate Slate forms the most prominent one. Some layers of slate appear to decompose much more readily than any phase of taconite. In the mines these slates may have become paint rock before the taconite in contact with them has lost its silica by leaching.

CHERTY TACONITE

Cherty taconite is a massive variety of taconite without any banding or slaty layers. As used here this term can be applied only in the study of drill cores in which only relatively short pieces of core are available. In the field exposures banding can be seen in most taconite, though the bands may be comparatively far apart. Therefore, strictly speaking, cherty taconite is a banded taconite, but its bands cannot be seen in drill cores

(Pl. V, D). All taconite is more or less cherty, but other features, such as banding for example, may be present and allow a more rigid classification of the phase.

Cherty taconite most resembles the irregularly banded taconite, but the latter phase can be distinguished by the twisted and wavy bands practically everywhere present. Cherty taconite has retained its original granule texture, but the granules consist of light gray or white chert and of iron oxides. This combination gives a grayish or brownish color to the rock as a whole, unless, as is rarely the case, a considerable portion of the granules consists of red jasper. The latter reddish phase has been called "jaspery taconite."

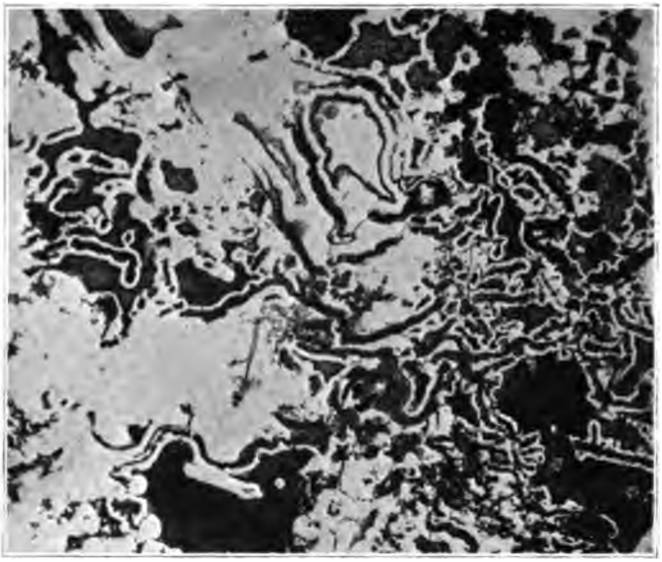
In weathering and leaching of cherty taconite, as in the similar banded and mottled varieties, pores and cavities develop. The rock becomes red or brown as a whole, but nearly white cherty areas may form where the taconite originally was very siliceous. It is especially noticeable in this phase of alteration that in some portions the silica is leached out and the iron oxides remain, while a short distance from such an area the reverse process seems to have taken place. Correlations of drill cores and field observations lead the writer to believe that in the case where white cherty areas have remained while the iron was leached, the iron was present in the pore spaces as iron carbonates or greenalite, both of which seem to be more easily attacked than the iron oxides.

GREENALITE TACONITE

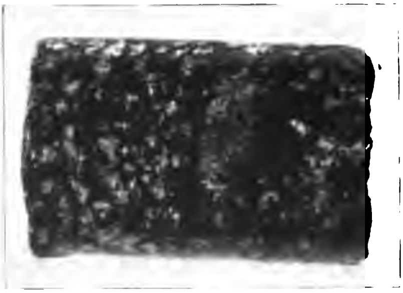
The distinction between greenalite taconite and cherty taconite is somewhat arbitrary and in the examination of cores was based on the color of the granules contained in the rock. The rock as a whole has a light greenish gray color due to the color of the granules which are chiefly made up of green amphiboles. The matrix of the granules, however, is chert as in cherty taconite, which differs from the greenalite taconite by the fact that its granules consist chiefly of darker iron oxides. All gradations from cherty taconite to greenalite taconite may be observed in drill cores, the classification depending entirely on the amount of the green silicates in the form of granules. Carbonates are also very common in the greenalite taconite.

As a rule greenalite taconite is rather uniform throughout, though frequently a band of dense dark cherty or slaty material is interbedded with it. The greenalite taconite usually has little magnetic oxide, but some shiny specks may be seen in most specimens. In some they are plentiful and such phases represent the gradations to the cherty or mottled taconite.

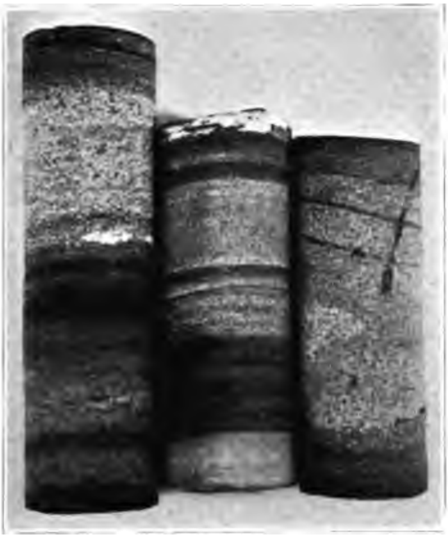
PLATE V



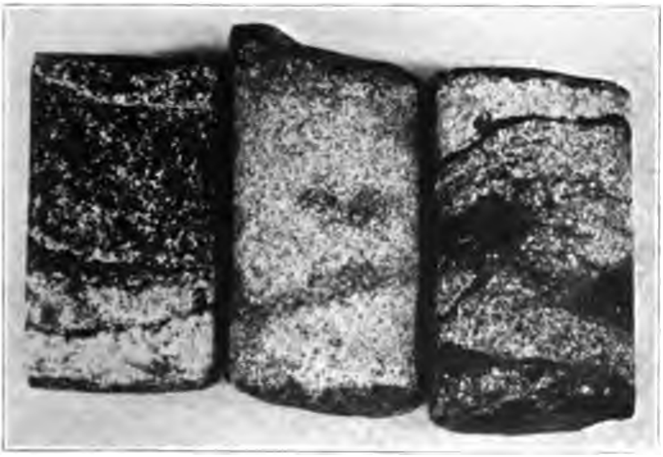
A. STRUCTURES PROBABLY ORGANIC IN A CHERT PEBBLE. DARK MATERIAL IS GREEN AND RESEMBLES GREENALITE. WHITE IS CHERT. X 26. SLIDE M 947



B. DRILL CORE OF MOTTLED TACONITE. DARK MATERIAL IS MAGNETITE.
NATURAL SIZE



C. BANDED TACONITE. THE BANDS CONSIST OF MAGNETITE AND SLATY MATERIAL. THREE-FOURTHS NATURAL SIZE



D. DRILL CORES OF CHERTY TACONITE. BLACK MATERIAL IS MAGNETITE. ONE AND ONE-FOURTH NATURAL SIZE

While the greenalite taconite may occur anywhere in the Biwabik formation, it is very rare in the lower 30 feet of the Lower Cherty division. It is much more common in the western half of the range than in the eastern. Decomposed phases are not easily distinguished from those of cherty taconite. They are sandy greenish yellow in the unbroken cores, and the crumbled material looks similar. The ore derived from greenalite taconite is not high grade.

SLATY TACONITE

The slaty taconite consists of layers which are similar to the slate described, but is much richer in oxides of iron. Therefore it is heavier in weight, and sparkling grains of magnetite or hematite may be observed in it. The individual bands may be yellow, red, purple, green, gray, or black and combined in such a way that the color contrast of adjoining bands is rather conspicuous. The bands may be very thin, or they may reach a thickness of one inch. Equally thin layers of greenalite, greenalite taconite, or cherty taconite are commonly interstratified with the slaty material.

In decomposing the greenalite layers generally become porous and disintegrate, and the slaty bands become softer and lighter in color. On still further decomposition the slaty bands become paint rock and the material interstratified becomes friable. The quality of the ore from this phase depends upon the amount of paint rock present.

The slaty taconite occurs in all of the divisions of the Biwabik formation and may locally be fairly rich in magnetite.

MOTTLED TACONITE

Mottled taconite has a characteristic spotted or mottled appearance (Pl. V, B). The spots range in size from one-sixteenth to one-half inch in diameter. Frequently they are of very irregular outline, not at all like greenalite granules. They are generally lighter colored portions of chert or more rarely of yellowish carbonate. The matrix consists generally of dark gray or brownish cherty taconite, especially rich in iron oxides around the lean "spots." They have no sharp borders like pebbles, but are apparently due to irregular replacement of the original minerals. Where leached, this rock has the peculiar "worm-eaten" appearance.

BANDED TACONITE

The banded taconite is intermediate between cherty taconite and slaty taconite. It contains too many bands of very fine-grained slaty material to be classed as cherty taconite, and too much of cherty taconite with granule texture to be called slaty taconite. (See Pl. V, C.)

The bands consist of very dense fine-grained material commonly containing much magnetite. Magnetite, however, is also abundant in the cherty material between the bands. The bands are straight but not quite as regular as in the slaty taconite. In the Upper and Lower Cherty divisions the banded taconite is important. Whether banded taconite forms high grade or medium grade ore depends on the composition of the bands. The more they approach slate in composition, the lower grade is the ore.

IRREGULARLY BANDED TACONITE

Irregularly banded taconite usually occurs in the Lower Cherty division in which it is the thickest magnetite-rich member.

This taconite differs from the banded taconite in which the banding is parallel by the irregular arrangement of the bands which are often not continuous, but pinch out or split, and curve in the most irregular manner or end abruptly. (See Fig. 3 and Pl. VI, A.)

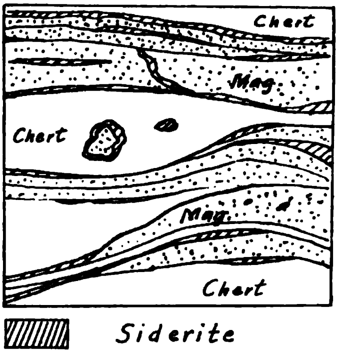
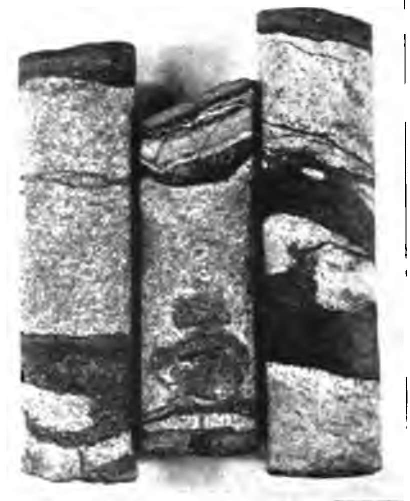


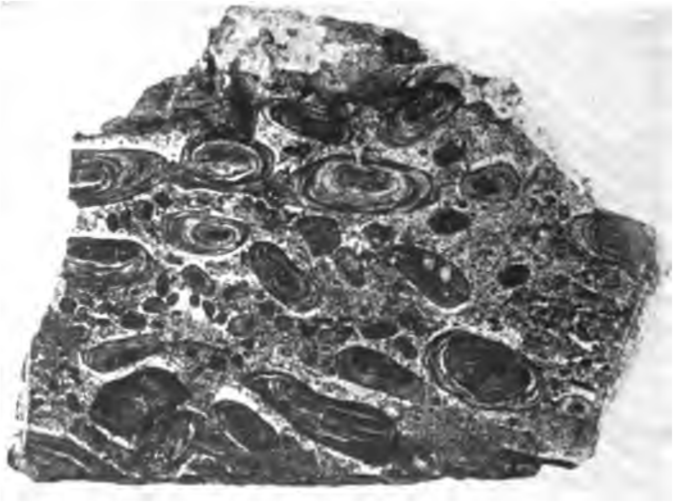
FIGURE. 3. IRREGULARLY BANDED TACONITE. MAGNETITIC BANDS (DOTTED) WITH NARROW SEAMS OF SIDERITE (SHADED) BETWEEN MAGNETITE AND CHERT. NATURAL SIZE. THICKNESS OF CARBONATE SEAMS SLIGHTLY EXAGGERATED

In iron-rich portions of the formation the bands are dark gray to black in color and consist of magnetite mixed with dense chert and carbonate. Between the dark bands lighter colored lenses and irregular areas of chert or carbonate are seen. Magnetite or hematite is sprinkled through these lenses and areas, giving a kind of "salt and pepper" effect. The dark bands hardly ever exceed two inches in width except on the East Mesabi, and generally are less than one inch wide.

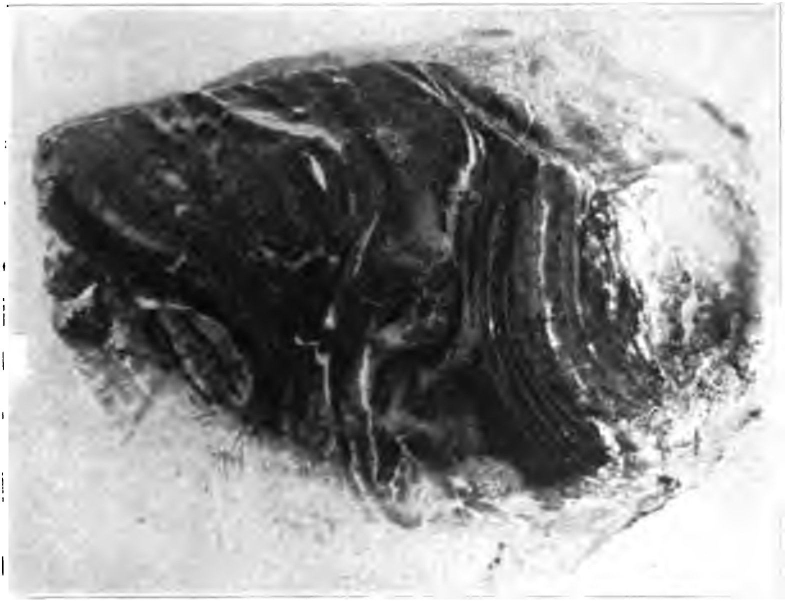
Usually three fourths of the iron oxides of the irregularly banded taconite are concentrated in these bands. The areas between the bands are considerably wider than the bands and are commonly lean in magnetite. In weathering or leaching the cherty portions turn white and



A. DRILL CORES OF IRREGULARLY BANDED TACONITE. BANDS CONSIST OF MAGNETITE AND CARBONATE. THREE-FOURTHS NATURAL SIZE



B. CONCENTRIC ALGAL STRUCTURES FROM THE BOTTOM OF THE LEONIDAS PIT. NATURAL SIZE



C. A MORE COMMON TYPE OF ALGAL STRUCTURE FROM THE TOP BENCH OF THE ADAMS PIT. NATURAL SIZE

innumerable holes up to the size of a match head form in it. Not uncommonly the cherty portions are disintegrated to a considerable extent, while the oxides of iron retain their magnetism. In such samples the magnetic iron runs especially high. On further decomposition the magnetite present is oxidized to hematite and most of the silica is removed. The resulting blue ore consists of bands of hard, heavy hematite, and sandy crumbling brownish or bluish portions between the bands. This is the best coarse blue ore of the Mesabi Range. The core from the irregularly banded taconite is usually very hard and well preserved in drilling.

CONGLOMERATES

Conglomerates may be divided into (1) that at the base of the Biwabik, (2) that in the Upper Cherty division, and (3) some scattered conglomeratic beds.

1. The basal conglomerate represents a break in deposition. This break may not have been caused by actual exposure of the sediments to erosion above the sea, but by a change of the conditions of deposition. The pebbles that can be seen in drill cores are naturally limited in size, and probably much larger ones exist that were not recognized in the samples. The pebbles comprise a great variety of rocks. In order of abundance, there are quartz, slate, chert, jasper, and a few magnetite pebbles. The slate pebbles are usually elongated, but the shapes of the others are varied. Subangular ones are as common as well-rounded ones. They are embedded either in a cherty or sandy matrix. Algal structures are closely associated with the conglomerate. They are found immediately above it and in the cherty matrix which surrounds the pebbles. The thickness of the conglomerate including the algal structures probably is never more than 10 feet, usually not more than 5 feet.

2. The conglomerate of the Upper Cherty division was first described by Wolff.[1] Grout and Broderick[2] found it a prominent horizon marker on the East Mesabi Range, and the present writer saw it east of Nashwauk in practically every drill hole and in many pits that penetrate the Upper Cherty division. It loses its significance as horizon marker west of Chisholm because it occurs in scattered layers at different horizons in the Upper Cherty division and even in the upper beds of the Lower Slaty division.

The pebbles of this conglomerate are small, as far as could be seen in the cores, and all consist of one of the phases of the iron formation. The most conspicuous are jasper and magnetite, though gray chert is also abundant. Their shapes are very irregular. Some are perfectly round and others very flat elongated. Usually their long diameters are more or less parallel to the bedding, but there are some striking exceptions.[3] The groundmass of the pebbles is usually cherty taconite or some gradational phase to greenalite taconite. Closely associated with the conglomeratic bed and adding to its value as horizon marker, are algal structures. The combined thickness of the conglomerate and algal structures west of Mesaba rarely exceeds 20 feet and may be as little as 2 or 3 feet.

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[1] *Op. cit.*, p. 243.
[2] *Op. cit.*, p. 20.

3. The scattered conglomerates are very erratic in occurrence. The size of the pebbles does not exceed half an inch. In places they seem to grade into granules of the size of greenalite. Their shapes differ widely. They are not angular, however. In composition they are like the phase of taconite in which they are embedded. A piece of drill core 2 inches long frequently may contain only one or two pebbles.

ALGAL STRUCTURES

Algal structures of the Biwabik were first described by Leith as "contorted banding."[4] The engineers of the Oliver Iron Mining Company had noticed these peculiar structures at an early date, but Grout and Broderick[5] were the first who assigned an organic origin to them. Photographs of outcrops of these structures in their paper show them much better than illustrations of drill cores could. The algal structures found in open pits are shown in Plates VI, B and C. The structures may be recognized by the fine contorted lines which resemble the grain of an especially gnarled and knotty piece of wood.

The lines are always thin and according to the way the structures are cut by the drill, they may appear as concentric bands enclosing very irregular cores or form little arches in which the lines converge on both limbs. Mineralogically the structures consist of very narrow red jasper or whitish chert bands which alternate with brown, gray, or black bands. Greenalite structures were not seen with these bands. All of them are surrounded by some cherty phase of taconite or conglomerate. Algal structures occur in the lower part of the Biwabik formation from one end of the range to the other without any apparent break, and also in the Upper Cherty division where they were observed as far west as Hibbing. (See Pl. II.)

Between Chisholm and Hibbing the algal structures of the Upper Cherty division are only locally seen. West of Hibbing they disappear entirely.

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[3] For illustrations, see Grout and Broderick, *op. cit.*, Pls. V, VI, and IX.

[4] Leith, C. K., Mon. 43, Pl. XII, A.

[5] Am. Jour. Sci., vol. 48, 1919, pp. 190-205.

While these structures are associated with some of the richest magnetite beds on the East Mesabi Range, this is not the case from Eveleth westward. Magnetite, while still present in these beds, becomes rather "spotty," and is not abundant west of Eveleth.

In the mines the algal structures, after they are once found in a bed, are not difficult to trace through the workings. The beds in which they occur are light, often almost white in color. They are dense and hard because they are composed of massive chert or jasper. The beds are very resistant to weathering, so that boulders of them are found even in the most highly concentrated ore in which other primary structures are destroyed. It is this property which makes the algal structures very valuable as horizon markers.

A word of caution is added here. Lines simulating algal structures often occur at the surfaces of joints. The true structures always penetrate the rock. It may be at first difficult to find the beds in place, but if one will look for "boulders" and broken pieces of them at the foot of the ore benches, one will soon discover the places where they were broken off.

SUBDIVISIONS OF THE IRON-BEARING FORMATION

Tabular Section of Divisions of the Biwabik Formation West of Mesaba Station

	Thickness in Feet
UPPER SLATY DIVISION	
Limy carbonate, with greenalite, greenalite slate, and slaty taconite	0 to 25
Slaty and cherty taconite, greenalite and slate	0 to 145
UPPER CHERTY DIVISION	
Cherty, banded, slaty, and greenalite taconite with layers of conglomerate. Algal structures. Some beds rich in magnetite	95 to 250
LOWER SLATY DIVISION	
Slaty taconite, greenalite, greenalite slate, banded and cherty taconite, carbonates and scattered conglomerates. Some rich magnetite beds	0 to 250
"Intermediate Slate." Black slate, greenalite slate, and paint rock	½ to 40
LOWER CHERTY DIVISION	
Lean member. White cherty and greenalite taconite, greenalite and greenalite slate	12 to 52
Member rich in magnetite. Irregularly banded, mottled, and greenalite taconite	90 to 250
Member with iron in ferric state	
Beds of cherty and banded taconite with slate and slaty taconite on top	8 to 70
Red basal taconite	0 to 40
Basal conglomerate and algal structures	0 to 12
Total	400 to 755

A tabular section of the thickness and character of the divisions is given above.

In subdividing the Biwabik formation, the divisions as introduced by Wolff are used. Grout and Broderick have given essentially the same divisions for the East Mesabi Range. Textural and mineralogical changes along the dip and strike in beds may lead to apparent discrepancies locally, and yet, taking into consideration the great thickness and length of the iron-bearing formation, its uniformity is remarkable.

LOWER CHERTY DIVISION

The Lower Cherty division is the most uniform division of the iron formation. This may be seen in Plate II, which is a longitudinal vertical section parallel to the strike of the iron formation. The thickness of the Lower Cherty division which is small in the eastern part of the range, is 140 feet at Mesaba and becomes progressively greater toward the west, reaching its maximum of 340 feet between Keewatin and Calumet, and from there to Prairie River it does not fall below 260 feet.

Prominent outcrops of the Lower Cherty division may be seen in the extreme northeastern extension of the Virginia Horn, 3 miles northeast of Virginia, (SE¼ sec. 28, T. 59 N., R. 17 W.), in the NW¼ sec. 34, T. 59 N., R. 18 W., 1 mile north of Mountain Iron, and along the high bluff north of Eveleth in sec. 20 and 29, T. 58 N., R. 17 W. It also has been exposed in the excavation along the road from Eveleth to Gilbert in sec. 5, T. 58 N., R. 17 W., and a few hundred feet northeast in the shallow cut of the Mesabi Electric Railway. A new cut may be found in the town of Eveleth where the concrete road to Virginia branches off from the city streets.

The Lower Cherty division may be subdivided into (1) the lower member with most of the iron in the ferric state, (2) the middle member rich in magnetite, and (3) the upper lean member.

1. The lower member includes the basal conglomerate and algal structures, the red basal taconite and cherty beds which nearly always have slate or slaty taconite beds on top. This member is usually 40 to 60 feet, but may become 80 feet thick. It is unimportant as a prospective magnetite horizon. The basal conglomerate, including the inseparable algal structures, is well developed from Buhl westward. From Buhl eastward to the big bluff between Virginia and Eveleth, it was observed in relatively few places. Farther east to Mesaba it gradually regains its prominence.

The so-called red basal taconite is easily traced from Aurora to the west end of the range. It may consist of any phase of taconite, usually of a combination of several, which are reddish in color. In spite of its gradual transition downward into the basal conglomerate and upward into the cherty beds, it is not easily overlooked because its color is so conspicuous and there are no other similar beds in the Lower Cherty division.

The cherty beds overlying the red basal taconite are also relatively easily identified, provided one knows that one is examining beds below the Intermediate Slate. These cherty beds also contain ferric iron, but so coarse as to be dark colored. They are separated from the usually magnetic beds above by a few inches of slate and a number of feet of slaty taconite which are almost invariably present at this horizon. The characteristic feature then is that a thin slate and slaty taconite as a rule separate the ferric oxides below from the magnetic oxides above them. There are places, however, in which some magnetite occurs in the beds below this slate.

2. The member rich in magnetite is of greatest economic interest on account of its possible availability in the future as low grade ore. It consists of irregularly banded taconite, mottled taconite, and greenalite taconite. The irregularly banded taconite is by far the most abundant. The amount of magnetite in the unoxidized parts of this member is probably 27 to 33 per cent, or in other words as much as on the East Mesabi Range. There is a difference, however, in the size of the grains and thickness of the bands of magnetite, in the two parts of the range, the East Mesabi magnetite being coarser and in thicker bands.

Not all of this member is as rich in magnetite as one might suppose after studying the longitudinal section, Plate II. In this section only deep holes are shown in which the Lower Cherty division is buried to considerable depth. Nearer the surface oxidation has affected large areas of this member. In some places almost all of it has been oxidized and little magnetite remains. Every gradation between the two extremes is found, though west of Snowball oxidation seems to have altered most of the magnetite that is close to the surface. At some places there is a leaching of the cherty material of the cores in advance of oxidation, with a corresponding increase in magnetite due to the removal of silica. As a whole, this member is the hardest part of the formation and therefore furnishes good, solid cores.

3. The "lean member" of the Lower Cherty division consists either of white cherty taconite and much decomposed material including yellow ore; or of greenalite taconite and yellowish carbonate.

The oxidation of this member is more advanced on the western half of the range as indicated in the longitudinal section. The white cherty taconite owes its color to the lean condition of the original beds and also to the extensive leaching out of the iron carbonate and green silicates.

The unoxidized beds of this member have a grayish green color due to the presence of much greenalite. Conglomerates are found in places but are neither conspicuous nor continuous. This member grades into the underlying rich magnetite beds. On the other hand, the contact between it and the overlying Intermediate Slate is the most definite line and horizon marker of the whole formation.

LOWER SLATY DIVISION

The Lower Slaty division has the very well-defined Intermediate Slate at its base, but the rest of the division has no horizon marker save conglomerates that occur either at the top of the division or much more often at the base of the Upper Cherty division in parts of the range. West of Nashwauk all conglomerates become very obscure or are absent altogether. At most places the presence of any cherty conglomerate will indicate the Upper Cherty or top of the Lower Slaty division.

The lack of a definite marker between the Lower Slaty and Upper Cherty divisions makes the dividing line between the two somewhat arbitrary. In this report, beds with a preponderance of slaty taconite were assigned to the Lower Slaty division; those beds with more cherty taconite than slaty were classed as belonging to the Upper Cherty division.

A discrepancy on account of this manner of dividing the Biwabik formation with the divisions introduced by Wolff[6] will be noticed for example in the drill hole from sec. 27, T. 57 N., R. 22 W. It was believed that the larger portion of the beds listed by Wolff as "Lower Slaty Horizon" were too cherty to be included in the Lower Slaty division, and they were classed with the Upper Cherty division. Wolff, on the other hand, makes the conglomerate shown at the base of the Upper Cherty horizon the dividing line. As these conglomerates are very erratic or are missing entirely at the western end of the range, they were not used as definite markers.

The Intermediate Slate consists of black slate, greenalite slate, and paint rock, or a mixture of these, and ranges from a few inches to nearly 40 feet in thickness. Its lower contact is almost always sharp and is usually marked by some black slate or paint rock. The upper contact is indefinite and a gradual change to other slaty phases takes place. The Intermediate Slate was seen in nearly all drill holes.

The Lower Slaty division, above the Intermediate Slate consists of layers of slaty taconite, greenalite, greenalite slate, and lesser amounts of banded and cherty taconite. These types are commonly interbedded in no definite order, save for the fact that the amount of iron in them decreases toward the bottom. As mentioned before, scattered conglomerates are common in the upper layers. The total thickness of the division is great in Range 15 and from Eveleth to Range 18. From there westward it gradually decreases and beyond Hibbing it is below 50 feet.

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[6] *Op. cit.*, p. 246.

West of Nashwauk only the Intermediate Slate is slaty enough to be included in this division.

Between sec. 6, T. 57 N., R. 17 W. (near Eveleth), and sec. 1, T. 58 N., R. 18 W. (near Virginia), a lens of cherty, banded and irregularly banded taconite rich in magnetite, and having a maximum thickness of 140 feet, occurs in the Lower Slaty division. In some respects its beds resemble the member rich in magnetite in the Lower Cherty division, but a great deal of the banded taconite is different from any other listed under this name. It consists of very thin, light colored, straight bands of cherty taconite which alternate with thin dark bands of cherty taconite in which magnetite has been concentrated. Therefore this phase has little resemblance to the ordinary banded taconite in which the dark bands are dense slaty material. This lens is 7 or 8 miles long.

Much of the high grade blue ore mined around Virginia and Eveleth is derived from this lens, while the rest of the Lower Slaty division produces yellow or brown ore. As a source of magnetite in this division only the lens of cherty taconite just mentioned deserves consideration.

UPPER CHERTY DIVISION

The Upper Cherty division is more nearly uniform in its general features than the Lower Slaty division. Its thickness ranges from 95 to 250 feet. Usually it is more than 140 feet thick, but west of Nashwauk it thins rather abruptly and regains a thickness of nearly 200 feet only at the town of Taconite. West of Taconite the cores of this division are insufficient and difficult to interpret. Between Kelly Lake and Nashwauk it cannot be distinguished from the Upper Slaty division, for the latter seems to have as much cherty taconite as the Upper Cherty division, which here is exceptionally slaty. Therefore the two have not been differentiated on the map for a distance of five miles.

The gradation of the Upper Cherty into the Lower Slaty division has been described. Besides cherty taconite and minor amounts of slaty taconite, the Upper Cherty division contains banded taconite, greenalite taconite, conglomerates, and algal structures. The conglomerate beds and algal structures are of chief interest. It was stated in describing the algal structures that they were generally found in, or very close to, a well-developed layer of conglomerate. The latter is really the most conspicuous conglomerate above the basal conglomerate, though probably not everywhere the thickest. The algal structures of the eastern half of the range are closer to the top, those of the western half nearer the bottom of the Upper Cherty division, though always at least 50 feet from either dividing line. The longitudinal section (Pl. II) should be seen for the exact location of the algal structures. West of Hibbing they enter beds included in the Upper Slaty division, and disappear altogether within a short distance. The conglomerate associated with the algal structures also becomes indefinite west of Hibbing.

There are other conglomerate beds above and below the algal structures in the Upper Cherty division, but none of them seems to be continuous over large areas. Correlation of them is impossible with the data available. All conglomerates become obscure and probably disappear entirely west of Nashwauk. The change from the Upper Cherty division to the overlying one is very gradual. As a source of magnetite the Upper Cherty division is out of consideration west of Eveleth. Oxidation and decomposition have converted most of the magnetite to hematite to considerable depths. The ore derived from this division is a high grade blue or brown ore.

UPPER SLATY DIVISION

The Upper Slaty division consists of slaty taconite, greenalite taconite, cherty taconite, and greenalite slate. A layer of limy carbonate occurs, usually interstratified with a little slate, at the top of the Biwabik formation. The carbonate where present in the solid cores forms a very good horizon marker. It is a well-crystallized, fine to medium-grained, white or gray rock, but evidently due to its inferior hardness, it has been lost in the drilling of many holes. Its greater solubility, also, probably caused more rapid decomposition. Without the carbonate as a guide no sharp lines can be drawn between the Biwabik formation and Virginia slate at some places, but the absence of any greenalite texture in about 10 to 15 feet of drill cores is almost always a sure sign of the Virginia slate. The limy carbonate was not seen west of Nashwauk. From there on no Upper Slaty division could be mapped, for while a thin layer of it may exist in places it was not possible to distinguish it in the disintegrated and decomposed material which predominates in the cores on the western end of the range.

The Upper Slaty division at most places is not thicker than 60 to 70 feet, though there is a marked increase near Hibbing. A few miles farther west it merges into the Upper Cherty division. (See map, Pl. I.)

Many layers of the Upper Slaty division are completely decomposed. Where silica has been leached out a low grade ore has formed. The beds of this division were originally lean in iron and they are valueless for purposes of magnetic concentration.

CORRELATION OF THE BIWABIK WITH THE GUNFLINT FORMATION

Broderick[7] has clearly stated the numerous points of similarity between the Biwabik and Gunflint formations. The fact that both can be divided into the same members, that both have two algal structure layers at corresponding horizons, and also the septaria bed, show that they were probably deposited at the same time as a continuous formation. For comparison a vertical section of the Gunflint area is included in Plate II. Broderick has proposed that the name Gunflint formation be dropped and Biwabik formation substituted, for the sake of simplifying nomenclature.

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[7] Broderick, T. M., Economic geology and stratigraphy of the Gunflint iron district, Minnesota: Econ. Geol., vol. 15, 1920, pp. 435-37.

CHAPTER IV

STRUCTURE OF THE IRON-BEARING FORMATION

GENERAL STRUCTURE

The Upper Huronian rocks of the Mesabi Range are simple in structure as is shown by maps and cross sections of Winchell, Leith, and others. The beds of the iron formation as a whole have been slightly inclined from their originally nearly horizontal position. They dip to the south and southeast at an angle of 4 to 7 degrees west of Eveleth (see cross sections Nos. 3 to 10, Pl. VII), and from 6 to 12 degrees east of Eveleth (see cross sections Nos. 1 and 2, Pl. VII). Between Aurora and the town of Mesaba, however, the dip is nearly zero in some areas. Due to this flattening of the beds between Aurora and Mesaba, the outcropping belt of iron formation in places becomes as wide as two miles.

The direction of dip in the Z-shaped bend of the Biwabik formation between Gilbert and Mountain Iron, which is called the Virginia Horn, is west and southwest for a few miles. The outlier of the iron formation 4 miles northeast of Virginia (sec. 35, T. 59 N., R. 17 W.) shows that the now eroded portion of the iron formation which covered the area of the Virginia Horn was nearly flat. This flattening of the dip is also indicated by the fact that the outcrops of the lower divisions of the formation are relatively wider than those of the upper divisions east of Eveleth as shown in Plate I. A flattening of the dip of the iron formation is also indicated by deep drill holes south of the range through the Virginia slate. In other words, there exists (partly eroded) a monoclinal flexure of the iron formation east of Eveleth, and the outcrops of the upper divisions of the iron formation are on the portion of the monocline which dips most steeply. This is shown diagrammatically in Figure 4. This monoclinal structure is simply an extension of the structures shown in reports by former investigators. Whether it exists, or once existed, west of Virginia is not known. The relatively great width of the outcrops of iron formation west of Virginia is due mainly to the slight dip of the formation. Rapid changes locally in this width may be due to either local changes in dip or changes in the thickness of the iron formation.

As would be expected in a brittle rock like taconite, joint and bedding plane cracks are exceedingly numerous throughout the formation. The joint surfaces as a rule are straight and, in places, of considerable length. The strike of the joints was taken on most exposures of the range and the following generalization has been derived from these measurements:

1. With relatively few exceptions, as in the case of exceedingly dense cherty taconite phases, three joint planes are present.
2. They are either at right angles, or nearly at right angles, to the bedding planes.
3. The directions of strike are approximately N. 10° E. for one set, east-west for another, and N. 45° W. for a third. Naturally there are many variations, but as a whole the agreement is conspicuous.
4. In slaty phases of taconite there may be two more sets of joints.
5. Joints in the underlying Pokegama quartzite are similar.

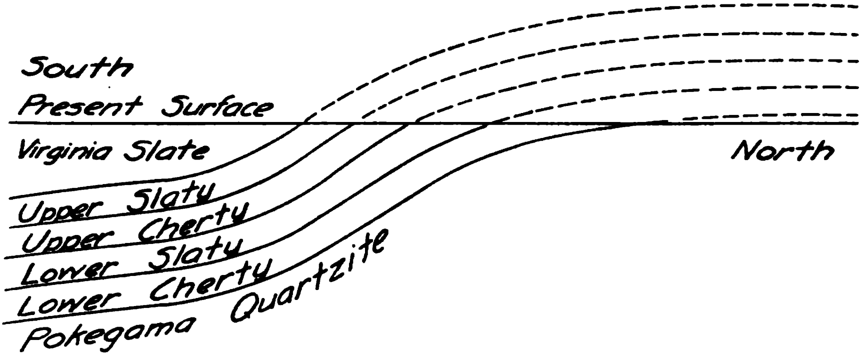

FIGURE 4. IDEAL NORTH-SOUTH CROSS SECTION OF THE IRON FORMATION BETWEEN GILBERT AND BIWABIK. VERTICAL SCALE TWICE THAT OF HORIZONTAL SCALE

SPECIAL STRUCTURES

A prominent monocline is exposed in the Alpena pit at Virginia. (See Fig. 5.) Its axis strikes north. The beds on the east of the monocline are about 400 feet higher than the corresponding ones on the west side. This fold was for a time regarded a reverse fault in earlier reports.

A normal fault is exposed in the Biwabik pit north of Biwabik. The strike of the fault appears to be nearly east-west along the north edge of the Biwabik formation. It has been traced eastward into sec. 5, T. 58 N., R. 15 W. The dip of the fault plane is steeply south. The displacement is at least 200 feet. Greenstone on the north is now in contact with iron-bearing rocks on the south side of the fault plane.

There are some special structures found in ore bodies which are discussed later. Some of them are due to slumping, but others originated before the concentration of the ore by weathering.[1] Among these are kaolin dikes, originally igneous intrusives. They are found as far west as Elba (sec. 18, T. 58 N., R. 16 W.). One dike has been reported from an old mine at Nashwauk, but its occurrence could not be verified.

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[1] A fault or monocline appears to be located between the La Rue and Hawkins mines at Nashwauk. Mr. John Edwin, engineer of the La Rue Mine, also called the writer's attention to this structure.

CHAPTER V

THE MAGNETITE DEPOSITS

MINERALS AND CHEMICAL COMPOSITION

The minerals in the areas rich in magnetite are essentially the same as those found in the unweathered formation as a whole. (See p. 8.) The magnetite frequently contains minute specks of hematite as inclusions. As hematite ore bodies are approached the amount of magnetite decreases usually abruptly, and hematite takes its place. This change is especially abrupt in the areas east of Mountain Iron.

The chemical composition of the average taconite as given by Van Hise and Leith[1] is as follows:

Fe	25.71
SiO_2	58.70
P	0.021
Al_2O_3	0.54
Loss on ignition	1.96

The present writer made a partial analysis of a typical sample of irregularly banded magnetite taconite and found

Fe	29.39
SiO_2	44.09

On the East Mesabi Range[2] the average sample of magnetite taconite from the Upper Cherty beds near Babbitt is: Fe 33.80, and SiO_2 45.17. This closely resembles the West Mesabi taconite. As on the East Mesabi, the amount of phosphorus in the magnetite taconite is very low as shown in the table on page 32.

TEXTURE

The magnetite in the taconite is practically all very fine grained. The individual grains are of microscopic size and as a rule show octahedral outlines of magnetite, though magnetite pseudomorphs after hematite are not uncommon.[3] The minute grains of magnetite may form aggregates with the outlines of greenalite granules (Pl. VIII, A.), or be concentrated into dense bands (Fig. 3). The dense bands, when viewed under the microscope, consist of minute grains of magnetite similar to those shown on Plate VIII, B, which are embedded in a matrix of carbonate and chert. Most of the carbonate is siderite. Plate VIII, B, shows the average size of the magnetite grains. In this photograph the grains are, however, only half as abundant as in the average dense band.

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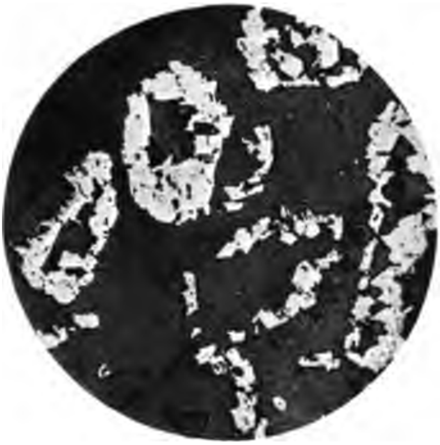
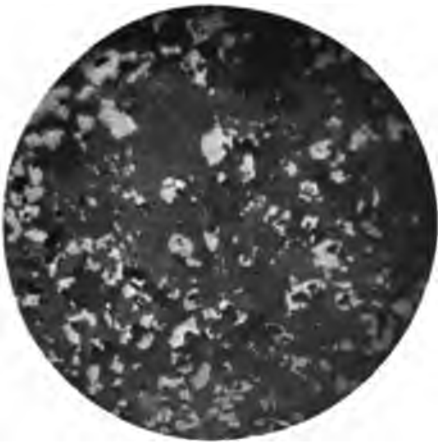
[1] Van Hise, C. R., and Leith, C. K., U.S. Geol. Survey Mon. 52, 1911, p. 181.

[2] Grout and Broderick, *op. cit.*, p. 29.

[3] Gruner, J. W., Paragenesis of the martite ore bodies and magnetites of the Mesabi Range. Minnesota: Econ. Geol., vol. 17, 1922 pp. 1-14.



A. EUHEDRAL MAGNETITE (WHITE) IN FORM OF GREENALITE GRANULES. X 40



B. EUHEDRAL MAGNETITE (LIGHT GRAY) IN GANGUE OF CARBONATE AND CHERT. X 200

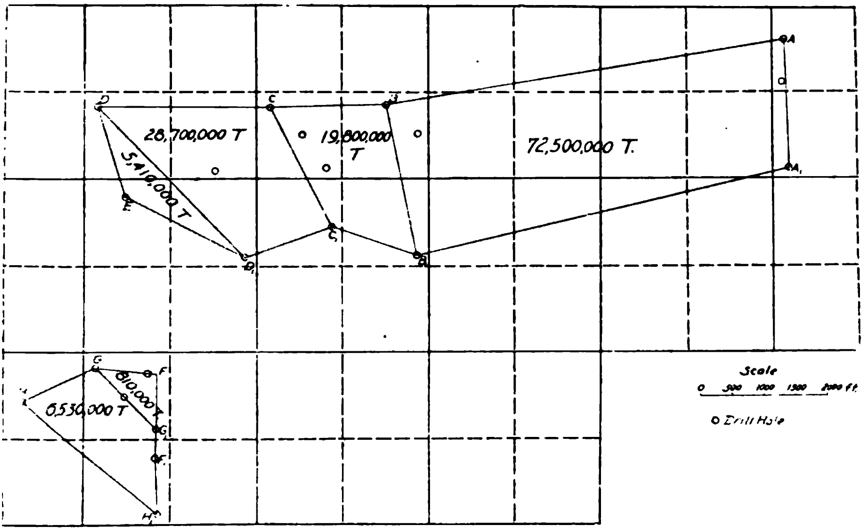


FIGURE 6. APPROXIMATE OUTLINE OF A MAGNETITE BODY BETWEEN MESABA AND BIWABIK

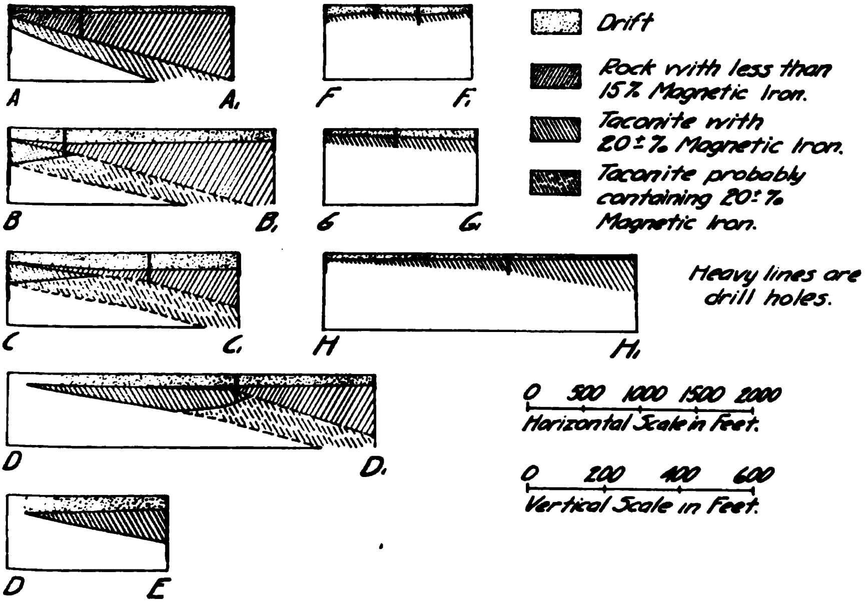

A
A1
B
B1
C
C1
D
D1
D
E
F
F1
G
G1
H
H1
Drift
Rock with less than 15% Magnetic Iron.
Taconite with 20±% Magnetic Iron.
Taconite probably containing 20±% Magnetic Iron.
Heavy lines are drill holes.
0 500 1000 1500 2000
Horizontal Scale in Feet.
0 200 400 600
Vertical Scale in Feet.

FIGURE 7. CROSS SECTIONS OF MAGNETITE BODY OUTLINED IN FIGURE 6

The magnetite may also be found as rounded spots or blotches with a chert or carbonate center, such as was described under "mottled taconite," on a preceding page. A great deal of the magnetite also occurs scattered through the cherty and slaty material. On the East Mesabi Range the magnetite is usually much coarser in grain and concentrated in thicker bands.

STRATIGRAPHY AND DISTRIBUTION OF THE MAGNETITE BODIES

In Chapter III the members of the formation rich in magnetite have been indicated. The following is a summary statement.

1. The most promising division of the Biwabik formation is the Lower Cherty division. Of this the only member which deserves consideration is the centrally located member consisting chiefly of irregularly banded taconite and to a lesser degree of mottled and greenalite taconite. This member is usually of great thickness and is uniform in iron content.

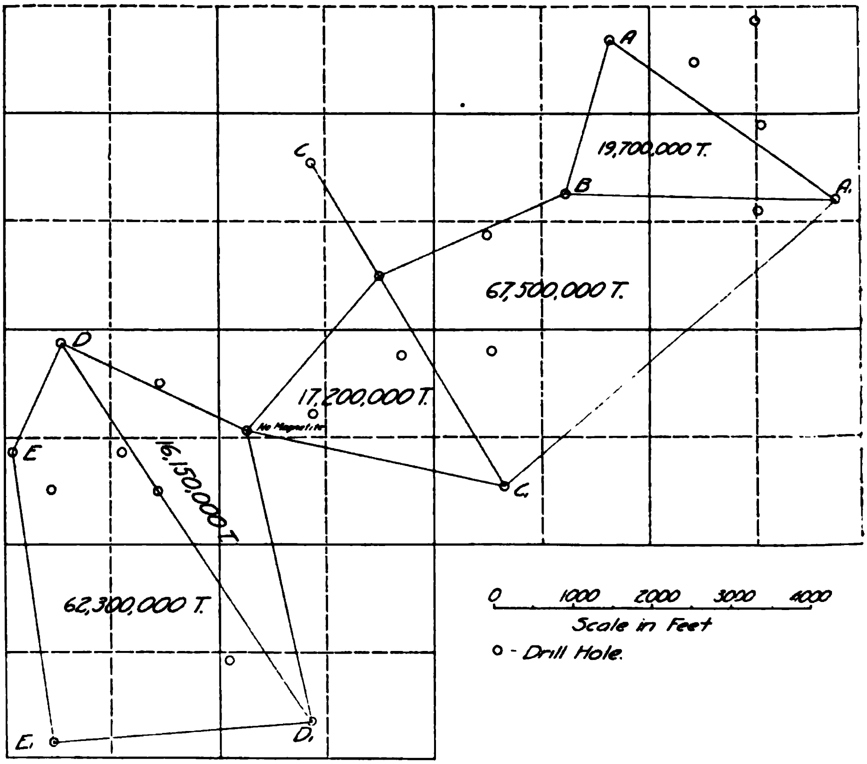


FIGURE 8. APPROXIMATE OUTLINE OF A MAGNETITE BODY BETWEEN CHISHOLM AND KEEWATIN

While it extends throughout the whole range (it is thin east of Mesaba) it holds no promise west of Snowball, because the magnetite is changed to higher oxides close to the surface west of this town. This change has also affected large areas in other parts of the range and it must not be expected that magnetite ore bodies will be found at the surface wherever this central member of the Lower Cherty division is in contact with the drift. It is possible that the exploration of a magnetite ore body, even in this rich member, would require almost as much drilling as that of a hematite body of an equal tonnage of metallic iron.

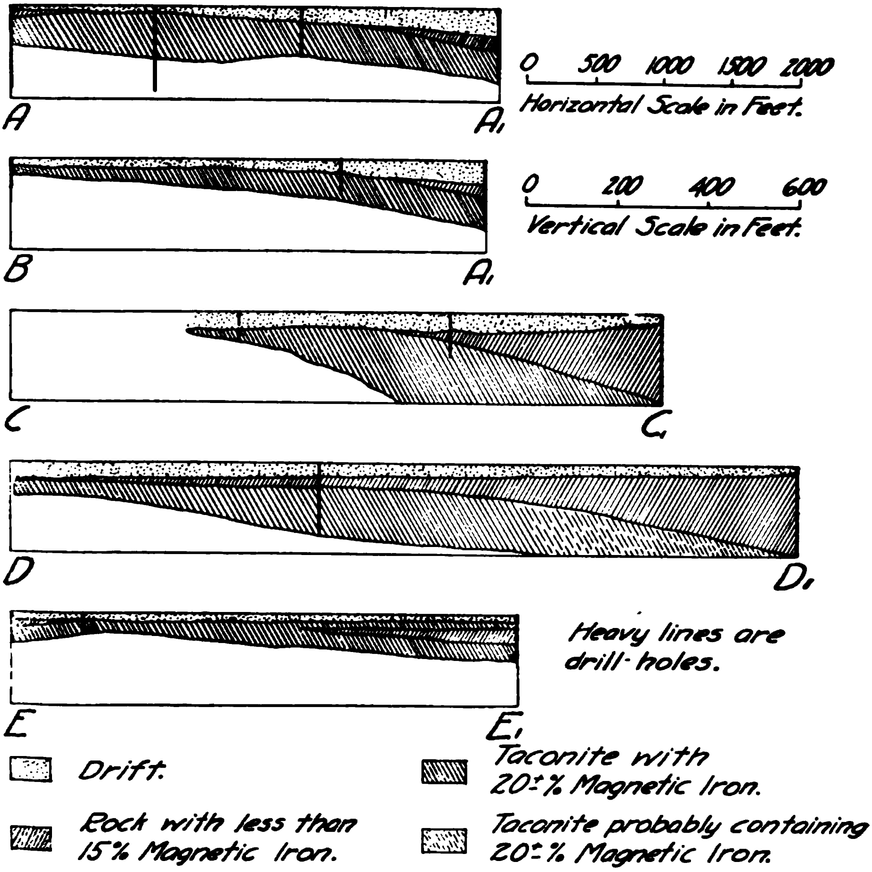

0 500 1000 1500 2000
Horizontal Scale in Feet.
0 200 400 600
Vertical Scale in Feet.
A
A₁
B
A₁
C
C₁
D
D₁
E
E₁
Heavy lines are drill-holes.
Drift.
Taconite with 20±% Magnetic Iron.
Rock with less than 15% Magnetic Iron.
Taconite probably containing 20±% Magnetic Iron.

FIGURE 9. CROSS SECTIONS OF MAGNETITE BODY OUTLINED IN FIGURE 8

2. The Lower Slaty division is either too thin or too lean to be a prospective magnetite horizon, except in the lens of irregularly banded and of banded taconite between Mountain Iron and Eveleth (p. 21). This lens is almost as high in magnetite as the rich member in the Lower

Cherty division. It also resembles it in texture in certain portions. It is of considerable thickness (Pl. II), and is low in phosphorus.

3. The Upper Cherty division is much less uniform in magnetite content than its stratigraphic equivalent of the East Mesabi Range, where it is mined at Babbitt. On the Central and West Mesabi Range magnetite occurs in it in a very erratic manner and changes of this mineral to hematite are very extensive. There is little promise of finding magnetite deposits of considerable size and thickness in it near the surface west of Gilbert. East of this town the possibilities are somewhat better, especially near Mesaba.

4. In the Upper Slaty division magnetite is scattered and is present in relatively small amounts. There is small probability that it will ever be mined.

GRADE AND SIZE OF THE DEPOSITS

The amount of iron as magnetite in the good sized taconite beds which are richest in magnetite varies between 20 and 30 per cent. The average is about 22 per cent iron in the form of magnetite. Five magnetic concentration tests were made on average samples of irregularly banded and mottled taconite of the Lower Cherty division. Each one of the samples represents five feet of drill core. The samples are from widely separated localities west of Mesaba. The tests were made by the Minnesota School of Mines Experiment Station, according to the method developed in testing East Mesabi taconite. The samples were crushed to pass through 150 mesh. The amounts are given in per cent.

Sample No.	Fe in Taconite	Fe Recovered by Magnetic Concentration	Fe in Concentrate	P in Concentrate
1............	31.34	30.90	67.94	0.007
2............	25.32	19.13	65.77	0.014
3............	31.12	22.97	68.68	0.005
4............	28.75	23.07	67.11	0.007
5............	31.57	17.65	66.44	0.007

Sample No. 5 is the only one which was leaner than was estimated with the aid of a horseshoe magnet. The writer had an opportunity to see analyses of other samples of cherty taconite. All were extremely low in phosphorus.

The size of the magnetite bodies depends on the limits placed on the quality of ore, the amount of overburden to be removed, and the depth to which open pit mining could be carried on. It is safe to assume that these bodies will not be drawn on soon, but it is not unlikely that they will be utilized some day. The available drill holes are insufficient to make any reliable estimates of the size of the magnetite bodies, but an attempt has been made to estimate the amount of iron that could be extracted from certain areas containing taconite with 20 or more per cent magnetic iron. The lower limit in these estimates was fixed arbitrarily as 200 feet below the top of the drift, but only taconite containing 20 per cent or more iron as magnetite was included in the estimates. Where drill holes stopped in such ore the probable total depth of the ore was estimated from the dip of the beds and included in the tonnage. Figures 6, 7, 8, and 9 are the bodies for which the tonnages were computed. The distortion of section lines was disregarded in the diagrams. The thin straight lines represent the boundaries of the areas, the small circles, the drill holes. It is not improbable that the areas are much larger than shown and the drift cover is less at some places, but there are not enough drill records available for exact determinations. As may be seen, the quantities of taconite with 20 per cent or more of iron in the magnetically recoverable condition range from 100,000,000 to 200,000,000 tons in each area. At greater depth than 200 feet the hematite becomes rarer and the ores contain the original amount of magnetite. Figure 10 is an actual cross section through the central part of the range. It illustrates how the magnetite bodies follow the dip of the beds.

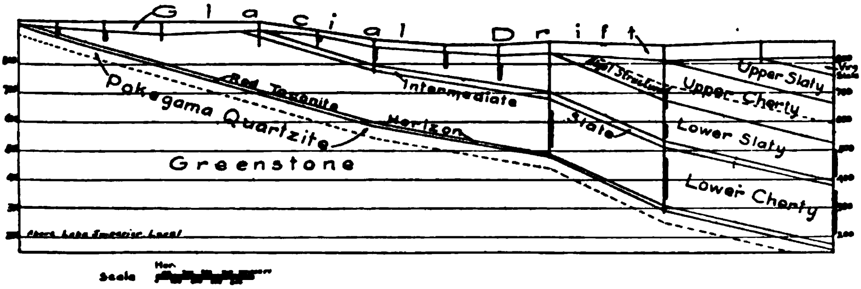


FIGURE 10. CROSS SECTION THROUGH CENTRAL PART OF THE MESABI RANGE SHOWING SUBDIVISIONS OF THE BIWABIK FORMATION AND ABUNDANCE OF MAGNETITE

It has been known for some time that the glacial drift is thinner above the Lower Cherty division than above the Upper Slaty division. In other words, the drift cover becomes thicker as a rule toward the south side of the iron-bearing formation. This fact is especially important for future exploration of magnetite bodies.

It was the practice in former years to keep only part of the drill cores in order to save storage room. It seems highly desirable to save all of the cores for future reference. Such a policy would undoubtedly repay the property owners and operators ultimately. Another common practice has been the dumping of strippings on the portions of the iron-bearing formation containing low grade ore and magnetite. It would be to the advantage of future generations to place the dumps on rocks older than the iron-bearing formation wherever possible.

CHAPTER VI

THE HEMATITE–LIMONITE DEPOSITS

ORES AND THEIR CHARACTERISTICS

In the papers by Winchell, Spurr, Leith, and Wolff the Mesabi ores are described in detail. According to Wolff[1] there are three kinds of ore: (1) a high grade blue or brown ore averaging, dry, 59 per cent of iron; (2) a medium grade brown or yellow ore averaging, dry, 55 to 56 per cent of iron; and (3) a low grade yellow or brown ore averaging, dry, about 50 per cent of iron.

The blue ore is a Bessemer ore found in the Lower Cherty division, in the Upper Cherty division, and in parts of the Lower Slaty division. The brown ore occurs in the various divisions except possibly in the Lower Cherty division. The yellow ore occurs at the top and, in parts of the range, at the bottom of the Lower Cherty division. The ore at the top is easily recognized where it is in contact with the red intermediate paint rock. The yellow ore may occur also anywhere above the paint rock, where the original rock consisted mainly of greenalite and carbonate.

It is possible to correlate the different ores with the unaltered members of the formation from which they were derived.[2] Examination of thousands of drill cores, and much microscopic study have shown that certain minerals on weathering practically always change to definite alteration products. For example, much magnetite in a drill core means blue ore in the corresponding horizon of an ore body. If a larger amount of slate is interlayered with the magnetite the ore becomes brown. Predominating greenalite or siderite in the rock, on the other hand, nearly always produces yellow ore. Much slate with the greenalite may make the yellow ore derived from them non-merchantable. Very lean greenalitic taconite, as it occurs in most parts of the Upper Slaty division, very rarely yields a commercial lean yellow ore. Black slate alters to ore only under exceptional conditions. Usually it forms the paint rock which is high in alumina and correspondingly low in iron.

Mineralogically stated, we may say that, in the decomposition of taconite, magnetite yields martite. Hematite remains unchanged. Greenalite and siderite alter to limonite which is brownish yellow when finely divided. Ferromagnesian minerals, which usually carry the iron contained in the slaty phases, yield limonite on decomposition, though it seems to be the rule that aluminous slates alter to hematite paint rock.

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[1] Wolff, J. F., Recent geologic developments of the Mesabi Iron Range, Minnesota: Lake Sup. Min. Inst., 1917, pp. 245-47.

[2] Gruner, J. W., *op. cit.*

Minerals in iron formation before weathering		Minerals in iron formation after weathering	Kind of ore
Virginia Slate		Slate or light colored paintrock	
Upper Slaty	Amphiboles Greenalite Slate Chert	Limonite Paint rock	Yellow ore
Upper Cherty	Amphiboles Chert Magnetite	Limonite Martite	Brown and blue ore
	Algal structures	Cherty boulders	
	Chert Magnetite Hematite Some slate	Martite Hexagonal hematite Paint rock	Blue and brown ore
Lower Slaty	Amphiboles Magnetite Slate	Limonite Martite Paint rock	Brown and yellow ore
	Amphiboles Greenalite Slate	Limonite Paint rock	Yellow ore
	Intermed. slate	Paint rock	
Lower Cherty	Greenalite Carbonate Amphiboles Chert Magnetite	Limonite Some Martite	Yellow and brown ore
	Chert Magnetite Some amphiboles and carbonates	Martite Some limonite	Blue and brown ore
	Slate	Paint rock	
	Chert Hematite Slate	Hematite Paint rock	Brown and yellow ore
Pokegama Quartzite		Quartzite stained by iron oxide	

FIGURE 11. DIAGRAM SHOWING KINDS OF MINERALS AND ORES DERIVED FROM TACONITE BY WEATHERING

The alumina itself combines with silica and water and forms kaolinite. These changes are shown in Figure 11, which shows an ideal case of alteration.

It was stated that blue ore occurs in three different divisions of the iron formation. The question arises whether it is possible from the physical characteristics of the blue ore, to identify the subdivision of the iron-bearing formation from which it is derived. It is believed that with some exceptions a fairly accurate determination can be made. The blue ore of the Lower Cherty division is coarser than most of the other blue ore, and it has very heavy, hard layers in it which are not straight but irregular and rough, and usually close together. They represent the originally magnetic layers of the irregularly banded taconite. The blue ore from the Upper Cherty division also contains layers but the layers are more porous and therefore lighter in weight. They are relatively smooth besides being comparatively straight and easily broken by hand. They represent original bands of a somewhat more evenly banded primary material.

The blue ore which is found in the Lower Slaty division in the central part of the range may be in part so similar to that of the Lower Cherty that it cannot be distinguished, but a great deal of it is finely banded. The bands are due to very narrow straight layers of hematite which formerly alternated with fine bands of silica. The latter have been removed, but the original structure has been fairly well preserved.

With regard to the wash ores of the western part of the range it is possible to use the same classification, if one bears in mind that the sandy silica still present gives a much lighter color to the ore. This silica is in the form of minute quartz grains, as can be seen with the aid of the microscope. It is possible that much of the cement between these quartz particles was originally a carbonate, which is more abundant in the unweathered cores on the western end of the range than farther east.

SHAPES AND STRUCTURES OF ORE BODIES

From the standpoint of the engineer ore bodies may be classified into the trough shaped ore bodies, fissure ore bodies, and flat lying ore bodies. This classification was given by Wolff.[3] To quote from his paper:

> While the trough ore body is the typical one, there are two other types, namely, the flat-layered body and the fissure-type ore body. The former is either the remnant left by the erosion of a former trough-body or it is an ore layer continuing down the dip from a trough-body. Usually a layer has a rock (slate) capping. The fissure-type ore body is an incompletely developed trough-body and is usually associated with a larger trough ore body.

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[3] Wolff, J. F., Trans. Lake Sup. Min. Inst., 1917, p. 236.

The most important type is the trough shaped body. In size it varies from that of a large fissure type to some that have a length of nearly one mile, a width of 1000 feet, and a depth of 200 to 400 feet. At some places two or more troughs run parallel for a distance, then converge and ultimately unite into one body. Some of the troughs intersect. These troughs are formed by the leaching of the silica out of the taconite and the creation of much pore space. The porous residual masses of iron oxides are unable to support the overlying burden of ore and rock and slump, with the consequent elimination of a large part of the pore space. As the original bedding planes are preserved to a considerable extent in spite of the movement of the ore downward, there is formed an easily recognizable synclinal structure of the ore between the rock walls which remain in their original position. Figure 12 is an ideal cross section through such a body.

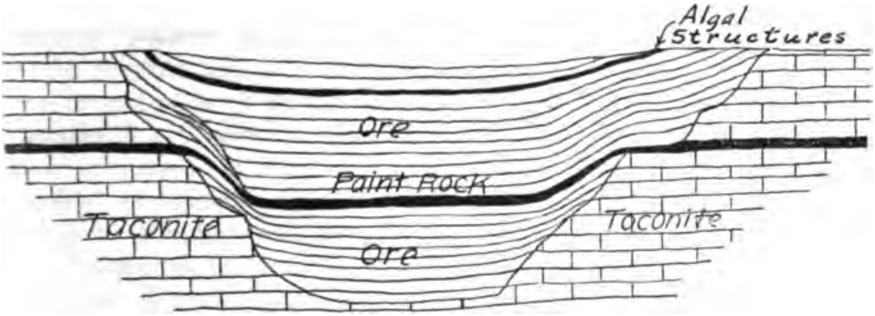


FIGURE 12. IDEAL CROSS SECTION THROUGH A TROUGH ORE BODY SHOWING SLUMPING OF ORE

The slump in the ore bodies is very considerable.[4] In a vertical column of solid taconite, originally 100 feet high, the shrinkage amounts to 40 feet if all the taconite is converted to ore. In other words, a thickness of 60 feet of ore is formed from 100 feet of taconite. There is some variation, of course, for slaty taconite, which undergoes less leaching and therefore less slumping than cherty taconite.

Paint rock layers in the ore at the edge of the trough ore bodies frequently form ideal planes along which slipping will take place. Such planes then resemble real slickensided fault planes characterized by gougelike material. Leaching has commonly affected a much larger area of taconite at the top of an ore body than near the bottom. This results in the narrowing of bodies toward the bottom. The slump under such

[4] Leith, C. K., and Mead, W. J., U. S. Geol. Survey Mon. 52, p. 188.

conditions may be steplike and characterized by terraces or offsets as shown in Figure 12. The direction and elongation of the troughs is practically always parallel to one of the major sets of jointing of the taconite.

The fissure ore bodies are very similar to the trough shaped bodies in every respect except size. The fissure bodies are also parallel to joint sets and were formed by the leaching of the taconite along joint fissures. Slumping is observed in them, but on a smaller scale than in the trough bodies depending upon the width and depth of the fissure body. The width may be only 2 or 3 feet, or even less, and the depth as much as 50 feet. The length may exceed 200 feet. These fissures do not necessarily reach the contact of the iron-bearing formation with the glacial drift. In places the ore body may have a roof of unleached taconite, and may not have slumped where the fissure is narrow.

Naturally the fissure bodies are commonly arranged in parallel lines like the joints which determined their position. Since there are several joint sets which intersect each other, fissure ore bodies also commonly intersect one another at corresponding angles. The best example of this type (Fig. 13) may be seen in the Malta pit near Sparta. Every intermediate stage between fissure bodies and trough bodies may be observed on the Mesabi Range. The numerous rock islands or horses seen in the larger pits represent the still unweathered taconite between former fissure bodies. There seems to be no doubt, then, that the trough body originated from fissure bodies by prolonged leaching between the fissures till most of the taconite had been converted into ore.

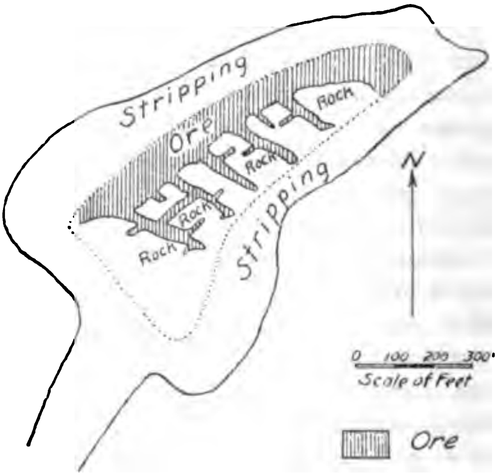


FIGURE 13. SKETCH PLAN OF FISSURE ORE BODIES IN MALTA PIT NEAR SPARTA

The flat lying ore bodies have been described by Wolff as "troughs cut off." As the name implies, they are of relatively great horizontal extent as compared with their thickness. In outline they are very irregular. Slumping, while present, is not conspicuous because the ore bodies are shallow and their transitions to the unleached taconite walls are gradual. It appears that leaching in these bodies followed chiefly the bedding planes of the sediments, while in the fissure and trough bodies leaching was most pronounced along the vertical joints. Due to the nature of the deposits it is impossible, however, to make any more specific statement. Many of the wash ore bodies of the western part of the range are flat lying bodies.

POSITION OF ORE BODIES IN THE IRON-BEARING FORMATION

In exploration work, only that part of the iron-bearing formation is included in the ore body which is commercially valuable. Much taconite, however, has undergone the same alteration though it is not far enough altered to form ore.

As previously reported, there is only a little ore south of the northern boundary of the Virginia slate. Where ore is discovered under the Virginia slate the slate is thin and highly decomposed to paint rock, which is very light in color on account of the small amounts of iron oxides in it. The thick Virginia slate being impervious to leaching solutions protected the iron-bearing formation effectively. Slaty phases of the Biwabik formation as a rule are too thin to have been of much influence in the guiding of solutions. They do not form the footwall or roof of ore bodies except in a few deposits. Usually the paint rock is highly fractured so that it is not impervious to solutions. In a few deposits, however, it appears as if the Intermediate Slate had prevented solutions from passing from the Lower Cherty division upward to the Lower Slaty, for at places yellow ore is found under the paint rock and taconite above the paint rock.

All other attempts to correlate the upper or lower limits of ore bodies with certain beds of the Biwabik formation show that the bottom and top of an ore body usually are very irregular, except that glacial drift commonly overlies a flat surface of ore. At a few places ore bodies extend into the Pokegama quartzite to a depth of several feet. Small vertical fissure bodies following joints may be traced between the flat lying beds for considerable distances, but then the roof above the ore fissure practically always shows some leaching and oxidation of the iron-bearing minerals to limonite and hematite.

LOCAL STRUCTURES OF THE ORE BODIES

For the discussion of local structures it is convenient to divide the range west of Mesaba into four groups:

1. The eastern group, the deposits between Gilbert and Mesaba.
2. The east central group, those between Gilbert and Mountain Iron inclusive.
3. The west central group, the deposits between Mountain Iron and a line half way between Keewatin and Nashwauk.
4. The western group, the deposits around and west of Nashwauk.

THE EASTERN GROUP

A number of rather irregularly shaped deposits belong in this group. Their longer axes seem to lie commonly in a northwest direction, which corresponds to the direction of prominent jointing, N. 40° to 50° W. The size of the deposits is relatively small with the exception of the Stephens and Biwabik properties. The structure of the Biwabik deposit is controlled by the east-west fault to which it is parallel. A number of decomposed dikes have been found in the various deposits. In the Stephens, one strikes northeast, and in the Miller, another has a similar trend. In the Mohawk, a dike strikes northwest; in the Belgrade, the direction of a dike is N. 30° to 40° W. The strike of the dike in the "Corsica-80" is not known.

The deposits seem to show no preference for any particular horizon of the iron formation, but are as common in the higher as in the lower divisions. The transition from the ore to unaltered country rock is fairly abrupt, resulting in steep rock walls as far as can be seen in the present open pits. Quartz veins with which manganese oxides are associated were observed in some of the mines. Their trend is rather irregular and frequently obscure.

THE EAST CENTRAL GROUP

In this group belong some of the deepest and most highly concentrated ore bodies of the range. There are two reasons for such depth and concentration: the iron formation reaches its greatest thickness in this area, and in addition to a Lower Cherty division with a high primary iron content, the formation possesses an unusually thick and rich Lower Slaty division. (See Pl. II.)

The longer axes of most of the large ore bodies lie in the direction of major joints and are perpendicular to the strike of the Biwabik formation. The walls of the bodies are unusually steep and sharply defined. The transition from ore to rock is accordingly abrupt and at some places in the lower divisions magnetic oxides reach to within a few inches of the walls of the ore. The ore bodies are either of the trough or fissure type. Commonly the bodies are not confined to one of the four divisions of the formation but penetrate two or more. The Leonidas and Missabe Mountain deposits, for example, extend vertically through the whole iron-bearing formation.

The algal structures can be studied especially well in this area and are a great aid in the working out of the structure of the deposits. (See Pl. IX.) In a few of the smaller mines, such as the Ordean, the algal structures seem to form the bottom of the ore. Perhaps the very dense and lean algal bed acted as guiding plane to solutions. In the Alpena Mine the algal structures are exposed in the nearly vertical strata between two ore bodies (now mined out). This bed is sharply folded into a monocline (Fig. 4). Here, as in many other places on the range, there is a noteworthy amount of secondary quartz which cements joint cracks and bedding planes. Such cemented beds are especially massive and resistant to weathering.

More conspicuous than these joint fillings are large quartz veins in this area which were mentioned on page 27. They seem to have had some influence on the structure of the ore bodies. In the Eveleth district a vein beginning in the northwest wall of the Leonidas pit was traced for nearly half a mile into the Adams pit. (See Pl. IX.) It follows the major jointing N. 80° W. Especially noteworthy is the fact that it marks the limit of the slump of the ore body on the south side for some distance. The beds north of the vein show the general dip of the iron-bearing formation, while south of it there is a decided break and steep dip to the center of the ore body. Another outcrop, possibly a continuation of the vein just described, is exposed in the East Adams and Fault pits. Here it is in the north wall of the ore body.

A similar vein, 12 to 24 inches wide, and striking N. 20° W. may be seen in the east wall of the Commodore pit. As it appears now after removal of the ore, this vein formed the boundary between the ore and the taconite. There is also a quartz vein 4 feet thick in the underground workings of the Hobart Mine at Gilbert. This vein strikes N. 40° W. parallel to major jointing. It is reported that practically no ore occurs on the northeast side of the vein.

A vein or dike 15 feet wide is exposed in the Fayal pit. It is parallel to the axis of the body from the southwest to the northeast wall. Where the "vein" itself cannot be seen, its place is taken by a shattered zone in the iron ore very high in manganese and intermingled with small pieces of kaolin. Under the microscope the quartz of this vein looks like highly altered igneous rock in a few places. It is stated that this dike did not penetrate upward through the Intermediate Slate.

Large irregular quartz veins were observed also in the Biwabik and Mountain Iron pits.

THE WEST CENTRAL GROUP

The chief difference between the east central group and the west central group is the strike of the deposits. The trend of the large majority of the trough bodies in the west central group is either northwest or west, therefore neither perpendicular nor parallel to the strike of the Biwabik formation as a whole, but usually parallel to one of the major joint sets. The ore bodies are relatively not so deep as those east of Mountain Iron, but many are of great areal extent. Several parallel troughs may form one large body. The deposits are found in the lower as well as in the upper divisions. The algal structures make an excellent horizon marker as far west as Chisholm. Between this town and the Hull-Rust pit at Hibbing, they are only locally well developed.

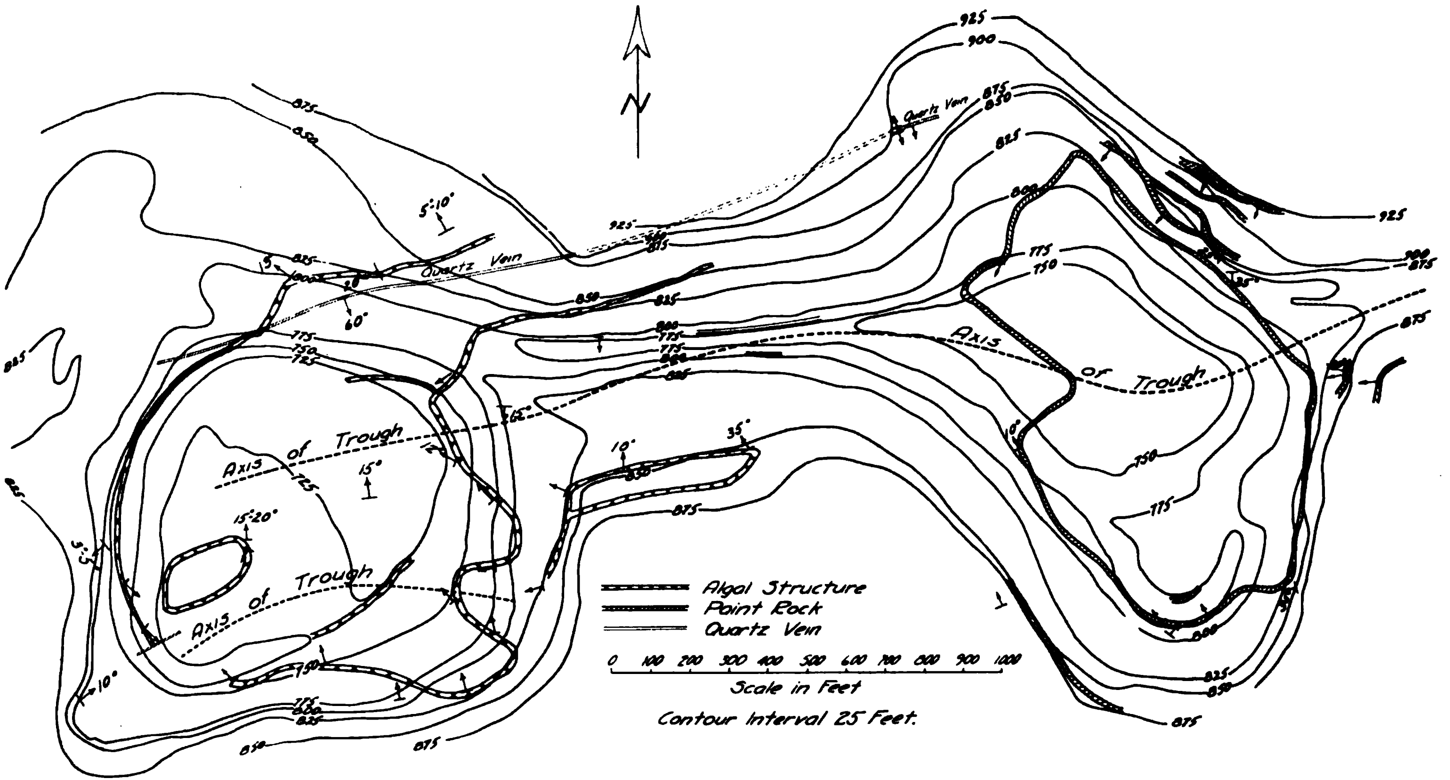
Unlike the group farther east, the transition from ore to wall rock is not quite so sharp in this group, with the result that the steep, sharply defined rock walls are not so common. Fissure bodies are not conspicuous. There is, however, plenty of evidence that leaching followed the jointing, though it was more extensive horizontally than vertically. Large quartz veins are found in some mines. Crystallized native copper was found in one of the large veins which cuts through the Dean and Wanless mines near Buhl.

Cretaceous conglomerate ore becomes important in some mines. It forms almost conformable layers with those of the iron-bearing formation and may reach a thickness of 30 and more feet, but usually is much thinner. The size of the pebbles of the conglomerate varies between that of coarse sand and boulders one foot in diameter. The smaller well-polished pebbles are limonite as a rule; the larger may be pieces of taconite. The conglomerates are generally little sorted, though there are exceptions. The cement between the pebbles is sandy or shaly material. Frequently it has a conspicuous scarlet or brick red color. Such conglomerate is high in phosphorus.

THE WESTERN GROUP

In this group belong most of the wash ore bodies that are mined at the present time. They are relatively shallow and usually belong to the class of flat lying bodies. Solutions probably advanced more along the bedding planes than along the joints in these deposits. Typical deep trough structures are rarely, if ever, developed, probably because the ore was leached only partially of silica and therefore has less pore space and shows less slumping. The transition from ore to wall rock is still more gradual than in the west central group. The trend of the ore bodies does not correspond to any particular set of joints. The deposits tend to be parallel to the strike of the formation. The Intermediate Slate which loses some of its usual distinctness is the only horizon marker.

PLATE IX



MAP OF ADAMS AND LEONIDAS PITS, SHOWING THE STRUCTURE OF THE TROUGH ORE BODIES AND THE POSITIONS OF THE INTERMEDIATE PAINT ROCK AND THE ALGAL STRUCTURES

Below it there occurs a characteristic lean, friable material which is too low grade in some places to make a wash ore. It is nearly white in many places and crumbles readily. Its thickness varies between a few inches and 30 feet.[5]

APPLICATION OF DETAILED STRATIGRAPHY IN THE EXPLORATION OF HEMATITE-LIMONITE ORES

It might appear that the exploration of the Mesabi Range has progressed to the stage at which the introduction of new horizon markers can be of little, if any, value. But even now, when most of the large ore bodies have been found, a careful study of the horizon markers in the drill cores and a plotting or replotting of them on the exploration sheets may reveal much new information. This study should also be extended to include the pits and underground workings of properties which have not yet been drilled thoroughly.

The value of the horizon markers is based on three considerations:

1. Originally before ore bodies existed the horizon markers which are now in the ore were at higher elevations; that is, they were in the same general planes and had the same general dip as their unleached continuations in the hard taconite which surrounds the ore bodies. Therefore, their slump practically always signifies the presence of ore beneath them. (See Pl. IX.)

2. As a rule, a given thickness of unleached taconite when changed to ore will yield a fairly constant thickness of ore on slumping. For example, 100 feet of taconite has slumped to yield 60 to 65 feet of ore in the larger deposits. In the wash ores about 70 to 75 feet of ore would represent an original taconite layer 100 feet thick. Therefore the amount of vertical slump of a horizon marker usually indicates the amount of ore beneath it.

3. The horizon markers like the Intermediate Slate, the algal structures, and the red basal taconite are practically always preserved even in ore highly concentrated and they are relatively easily recognized.

The mapping of the algal structures, for example, supplied knowledge of structure at one property. In examining shallow drill holes in the upper half of the somewhat weathered Biwabik formation it was found that they penetrated the algal bed. On plotting the algal bed a considerable sag or synclinal structure was noticed, which had escaped the attention of former explorers. Deeper drilling is justified in this area.

At many places it was possible by comparison of the height of a horizon marker in the walls of pits with the elevation of the same marker in the ore to estimate the amount of ore underlying the marker. When these results were checked it was found that they were fairly accurate. There probably is no other iron-bearing district in which horizon markers would give more important and reliable information than on the Mesabi Range. But this knowledge of position and size of ore bodies is not the only information derived from detailed stratigraphy. The kind of ore to be expected at a certain depth is equally important and can be foretold by the study of the horizon markers. It was pointed out on page 34, and in Figure 11, that each phase of taconite on leaching produces a distinct type of ore. As the longitudinal section, Plate II, gives the phases of taconite and the thickness of each throughout the range, it also indicates the kind of ore and the possible maximum or minimum thickness that may be expected in a certain area.

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[5] Some of the wash ore contains a little magnetite mixed with martite grains, but the amount of magnetite found in testing six 40-pound samples is negligible.

CHAPTER VII

THE ORIGIN OF THE IRON FORMATION[1]

PREVIOUS VIEWS ON THE ORIGIN[2]

H. V. Winchell[3] in 1892 concluded that the iron formation consists of chemical and mechanical oceanic deposits. N. H. Winchell[4] in 1899 accepted Spurr's[5] hypothesis that the iron formation was a glauconite-like formation, but later he[6] proposed that the greenalite resulted from a volcanic sand. Leith[7] objects to Spurr's glauconite hypothesis and thinks that colloidal silica may have combined with ferrous iron to form greenalite. He concludes: ". . . that the greenalite granules may possibly have developed directly from the abstraction, through the agency of organisms of iron from solution in sea water, whence it was contributed from adjacent land areas. . . ."

Van Hise and Leith[8] in 1911 concluded that all the important Lake Superior iron-bearing formations are very similar in origin. They believe that a very large part of the iron and silica was contributed to the ocean directly, either by magmatic emanations from igneous rocks (probably poured out on the ocean floor), or by rapid decomposition of basic igneous rocks, due to their contact, while hot, with sea water. Van Hise and Leith, however, think that considerable portions of the iron and silica may have been derived from the land by processes of ordinary weathering.

Wolff[9] believes that the bulk of the iron oxides in the Biwabik formation are in the same "chemical state" now as that in which they were laid down, and that greenalite was relatively unimportant as original mineral. Grout and Broderick[10] in discussing the deposition of ferruginous cherts, are inclined to believe that deposition took place in shallow water, mainly by organic agencies.

[1] This chapter is an abstract of a paper published in Econ. Geol., vol. 17, 1922, pp. 407-60. Descriptions of chemical experiments and references will be found there.

[2] For older literature see Leith, C. K., *op. cit.*, p. 31.

[3] *Op. cit.*, pp. 138-46.

[4] Winchell, N. H., The geology of Minnesota: Geol. Nat. Hist. Surv. Minn., Final Rept., vol. 4, 1899, p. 359.

[5] *Op. cit.*, p. 242.

[6] Winchell, N. H., Structural and petrographic geology of Minnesota: Geol. Nat. Hist. Surv. Minn., Final Rept., vol. 5, 1900, pp. 990, 997.

[7] *Op. cit.*, pp. 242, 254, 257.

[8] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior Region: U. S. Geol. Survey Mon. 52, 1911, p. 499.

[9] *Op. cit.*, pp. 233-35.

[10] *Op. cit.*, p. 46.

In a discussion of the iron formation it is necessary to consider (1) the solution of iron and silica in natural and artificial solvents, (2) the sources of the iron and silica for the formation of the Biwabik iron formation, and (3) the deposition of the iron and silica.

SOLUTION OF IRON AND SILICA

AMOUNTS OF IRON AND SILICA IN NATURAL WATERS

The average river water contains less than one part per million of iron.[11] Sea waters also are very low in iron. This suggests that such waters are an inadequate source for the deposition of a great iron-bearing formation. There are, however, some analyses showing more iron. The rivers of Brazil and other parts of South America carry from 2 to 7 parts of Fe_2O_3; this is a relatively large percentage of their total mineral content, which is usually low.[12]

Swamp waters commonly contain more iron than other surface water.[13] Moore[14] reports three waters with 47 to 61 parts of Fe_2O_3 per million, either from lakes in which iron ores are in the process of formation, or from creeks tributary to such lakes. Simpson[15] mentions a small stream which contains 17 parts per million of iron and much organic matter. It is noteworthy that organic matter seems to be always present in surface waters that contain much iron.

Spring waters often carry iron, but such waters are probably not the sources of the large iron-bearing formations, on account of their limited quantity. Silica is relatively abundant in many rivers and spring waters.

EXPERIMENTAL DATA ON THE SOLUTION OF IRON AND SILICA[16]

Experimental data show that iron minerals are soluble in weak acids but not in alkaline solutions. Carbonic acid (H_2CO_3) takes iron into solution as a bicarbonate of iron, but this bicarbonate is not stable in the presence of air which oxidizes the iron to the ferric form. Ferric iron is precipitated as limonite as a rule. It appears, therefore, that large amounts of iron cannot be carried by river waters as bicarbonate. Other acids, like sulphuric acid, which plays an important part in many geologic processes, do not enter into the transportation of iron over long distances.

[11] Clarke, F. W., The data of geochemistry: U. S. Geol. Survey, Bull. 695, 1920.

[12] Clarke, F. W., *op. cit.*, pp. 90-92. See also analyses *B* and *E*, p. 77; *G*, p. 93; and *E*, p. 105, which contain unusual amounts of iron and organic matter.

[13] Endell, K., Der Säuregehalt des Moorwassers: Jour. prakt. Chem., vol. 82, pp. 414-22, 1910. See also Endell, K., Uber die chemische und mineralogische Veränderung basischer Eruptivgesteine bei der Zersetzung unter Mooren: Neues Jahrb. Min., Beilage Bd. 31, 1911, pp. 1-54.

[14] Moore, E. J., The occurrence and origin of some bog iron deposits in the district of Thunder Bay, Ontario: Econ. Geol., vol. 5, 1910, pp. 528-38.

[15] Simpson, E. S., Notes on laterites in western Australia: Geol. Mag., vol. 49, 1912, p. 405.

[16] For a full discussion see: Econ. Geol., vol. 17, 1922, pp. 422-46.

It was pointed out that organic matter seems always to be present in river water carrying appreciable amounts of iron in solution. Chemical experiments[17] show that waters containing organic matter (commonly called humic acid) are powerful solvents of iron. Still more important, however, is the fact that iron dissolved in such waters cannot be entirely precipitated by inorganic means to which we often attribute its deposition. Iron bacteria and other micro-organisms seem to be the only efficient natural agencies of precipitation of iron in waters containing organic matter.

Silica in silicates is dissolved by dilute acid as well as alkaline solutions.[18] Quartz and chalcedony, however, are less soluble than silicates. Organic solutions, as used in experiments in the solution of iron, are also strong solvents of silica. Silica may be transported long distances as a colloid in solution, especially if organic matter is present.

SOURCES OF IRON AND SILICA FOR THE IRON FORMATION

ORIGINAL EXTENT OF THE IRON FORMATION AND AMOUNT OF IRON INVOLVED

For the discussion of the sources of iron and silica deposited in the Biwabik and Gunflint formations it is necessary to make an estimate of the original extent of the formations. The total length of the Mesabi and Gunflint ranges from a point west of Pokegama Lake to North Lake, Canada, is about 175 miles. The widths of the ranges vary considerably. The Biwabik formation has been identified in a drill hole at a depth of 2200 to 2700 feet, about five miles south of the town of Biwabik. The area of the Biwabik formation not covered by the Virginia slate has been estimated as 135 square miles; that of the Gunflint formation does not exceed 10 square miles. Assuming much erosion and the gradual thinning out of the formations, the total area originally covered by the Biwabik and Gunflint formations may be conservatively estimated as 5000 to 10,000 square miles. If, as supposed by some, the iron formation extended across Lake Superior, then the area covered was much greater. Probably 550 feet would represent the average thickness of the exposed Biwabik formation. For a sheetlike sediment with an area of 5000 to 10,000 square miles, an average thickness of 330 feet may be a fair estimate. The explored portion of the iron-bearing formation contains an average of a little more than 25 per cent iron and has a specific gravity of 3.0 to 3.1. The total amount of iron in 10,000 square miles of formation 330 feet thick would be nearly 2,000,000 million metric tons.

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[17] Gruner, J. W., *op. cit.*, p. 422.

[18] See also Lovering, T. S., The leaching of iron protores: Econ. Geol., vol. 18, 1923, pp. 523-40.

POSSIBILITY OF DIRECT CONTRIBUTION OF SILICA AND IRON FROM MAGMA

Association of Lavas with Chert

Van Hise and Leith[19] based their argument, that probably the greater part of the silica and iron of the iron-bearing formations had been contributed directly from the magma or from hot lavas poured out on the ocean floor, on the frequent association of basic igneous flows with chert and jasper. Their best evidence seems to be the discovery, near Hudson Bay, of chert and jasper grading into basalts of Algonkian age. Leith[20] says that this jasper must have been deposited "under conditions differing radically" from those observed today.

In California, radiolarian cherts are associated with basalts, some of which are spheroidal and ellipsoidal.[21] Geikie[22] mentions a number of occurrences of pillow lavas and interstratified cherts. Of the cherts of the Lower Silurian (Arenig group) of Scotland he says:[23]

> It thus appears that during the volcanic activity there must have been intervals of such quiescence, and such slow, tranquil, sedimentation in clear, perhaps moderately deep water, that a true radiolarian ooze gathered over the seabottom. . . . Thus the great depth of strata which elsewhere constitute the Upper Arenig and Lower and Middle Llandeilo subdivisions is here represented by only some 60 or 70 feet of radiolarian cherts.

It has recently been pointed out by Davis[24] that pillow lavas are also intrusive, and not necessarily submarine flows. Davis presents many arguments in favor of, and against, the direct contribution theory of silica. Dewey and Flett[25] believe that pillow lavas are usually accompanied by radiolarian cherts, and that the silica of the cherts was derived directly from the magma.

Scrivenor,[26] on the other hand, thinks that this hypothesis is not applicable to many East Indian cherts which are probably algal cherts, but lays stress on the removal of silica by tropical weathering.

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[19] *Op. cit.*, p. 499.

[20] Leith, C. K., An Algonkian basin in Hudson Bay—a comparison with the Lake Superior basin: Econ. Geol., vol. 5, 1910, p. 242.

[21] Ransome, F. L., The eruptive rocks of Point Bonita: Bull. Dept. Geol. Univ. California, vol. 1, 1893, p. 109.

Lawson, A. C., Sketch of the geology of the San Francisco Peninsula: Fifteenth Ann. Rept. U. S. Geol. Surv., 1895, p. 420.

[22] Geikie, A., The ancient volcanoes of Great Britain: London, 1897, vols. 1 and 2.

[23] *Op. cit.*, vol. 1, p. 198.

[24] Davis, E. F., The radiolarian cherts of Franciscan group: Bull. Univ. Calif., vol. 11, 1918, p. 404.

[25] Dewey, H., and Flett, J. S., On some British pillow-lavas and the rocks associated with them: Geol. Mag., vol. 48, 1911, pp. 202-9, 241-48.

A recent paper by E. Sampson (The ferruginous chert formations of Notre Dame Bay, Newfoundland: Jour. Geol., vol. 31, 1923, pp. 571-98) favors the inorganic origin of cherts. Their association with lavas is pointed out.

[26] Scrivenor, J. B., Radiolaria-bearing rocks of the East Indies: Geol. Mag., vol. 49, 1912, p. 247.

Magmatic Springs or Submarine Lava Flows Possible Source of Silica

If direct contribution of silica from the magma is assumed, the present writer favors the hypothesis of the derivation of silica from hot submarine lava flows rather than from magmatic springs, for two reasons:

1. If we assume a siliceous water with 1000 parts of SiO_2 per million (a much more concentrated solution than those of geysers), over 524,000 cubic miles of solution would have been necessary to transport the silica of the Biwabik formation (of 10,000 square miles area and 330 feet thickness). Such a quantity would cover an area the size of the United States to a depth of 900 feet. The magma which could furnish so much aqueous solution would probably have to be 20 to 40 times 524,000 cubic miles in volume,[27] the equivalent of a cone with an altitude equal to the radius of the earth, and a base 10,000 square miles in area.

2. On the other hand, if we imagine hot lavas poured out on the ocean floor, there must have been tremendous chemical reaction and physical disintegration. Disintegration would not contribute colloidal silica directly to the water; but diatoms (and probably other organisms), as has been shown by Murray and Irvine,[28] can abstract silica from detrital material.

The chief objection to the theory of contribution of silica to the sea by hot lavas, in the case of the Biwabik and Gunflint formations, is that contemporaneous igneous rocks have not been found within a considerable distance. Van Hise and Leith[29] noted this, and thought that the remarkable uniform character of the Biwabik and Gunflint formations was possibly due to their distance from contemporaneous igneous activity. The iron-bearing formation of the Gogebic Range,[30] which was in or near the area of igneous activity, is much like that of the Biwabik. The iron-bearing formation of Hudson Bay[31] and the Belcher Islands,[32] in which basalts occur with the sediments, is also very similar to the Biwabik formation.

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[27] Gautier's figures for the amount of combined water in granite are about 2.5 to 3.0 per cent in "The genesis of thermal waters and their connection with volcanism," abstract by F. L. Ransome in Econ. Geol., vol. 1, 1906, p. 691.

[28] Murray, J., and Irvine, R., On silica and siliceous remains of organisms in modern seas: Proc. Roy. Soc. Edinburgh, vol. 18, 1891, p. 245.

[29] *Op. cit.*, p. 517.

[30] Hotchkiss, W. O., Geology of the Gogebic Range and its relation to recent mining developments: Eng. and Min. Jour., vol. 108, 1919, p. 501.

[31] Leith, C. K., An Algonkian basin in Hudson Bay: Econ. Geol., vol. 5, 1910, p. 227.

[32] Moore, E. S., The iron formation on Belcher Islands, etc.: Jour. Geol., vol. 24, 1918, pp. 412-38.

Contribution of Iron from Hot Springs

The evidence seems to show that iron and silica in the ratio found in the Biwabik formation cannot be carried in any but very weak solutions. Clarke[33] cites many analyses of spring waters high in silica and others high in iron, but no water high in both. As a matter of fact, these two elements seem to be mutually exclusive except in very weak solutions. In acid waters which are high in iron, aluminum seems to be equally or more abundant, but this element is only sparingly present in the iron formation. Silica is present to only a very minor degree in the more acid waters, as would be expected and as has been demonstrated by many experiments.[34] It is difficult to conceive of an acid ocean or even of an acid, large inland sea. The acidity would quickly be reduced by the presence of many base-forming elements in the rocks, and unless the acidity were reduced temporarily or periodically, no iron could be precipitated. Of course, we could imagine acidity around the submarine hot springs and neutralizing conditions at some distance, where deposition occurred. Even then the probable presence of much aluminum and other metals in the solutions and the small amounts of silica would probably preclude the precipitation of ferruginous chert.

Solutions charged with carbonic acid can carry iron and silica. Iron as bicarbonate could be present in such cold solutions to the extent of 100-150 parts per million,[35] if other salts were absent. Their presence as bicarbonates necessarily would repress the solubility of iron.[36] In hot solutions bicarbonates can exist only when pressure prevents the escape of carbon dioxide. It is obvious that this gas would have been expelled as soon as the solutions reached an open, probably shallow basin. Iron would have been precipitated immediately. Even if only a part of the carbon dioxide had escaped, from either hot or cold solutions, it would have resulted in the formation of normal carbonates like those of sodium[37] and magnesium. These are alkaline toward litmus, and precipitate iron from solution. It probably would have necessitated special currents in the sea to carry these precipitates a hundred or more miles.

Assuming that a bicarbonate solution with 100 parts of iron per million (which would require 300 parts of SiO_2 to be in the ratio of iron to silica in the cherts—more silica than probably can be held in such solution except under great pressure), we find that it would take about 630,000 cubic miles of solution to furnish as much iron as is assumed to be in the Biwabik formation. An area the size of the United States could be covered with this volume to a depth of over 1000 feet. It does not appear probable that so much aqueous solution could come from a limited area.

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[33] *Op. cit.*, pp. 174-95.

[34] Leuhner, V., and Merrill, H. B., The solubility of silica: Jour. Am. Chem. Soc., vol. 39, 1907, p. 2630.

[35] Smith, H. J., On the equilibrium in the system—Ferrous carbonate, carbon dioxide and water: Jour. Am. Chem. Soc., vol. 40, 1918, pp. 879-85.

[36] Repression of solubility by a common ion.

[37] Smith, Alex., General chemistry for colleges: New York, 1920, p. 462.

Derivation of Iron from Hot Lavas

Van Hise and Leith[38] heated fresh basalt to 1200° C. and then plunged the mass into salt water. The violent reaction ensuing produced principally sodium silicate, but relatively little iron. They say that "the experiment does not seem to suggest an adequate source for the iron in this reaction." Igneous rocks in hot or cold water react alkaline,[39] for potassium and sodium silicates (water glass) are strongly alkaline. Therefore, it seems improbable that much iron will go into solution when hot lavas come into contact with sea water, even if some hydrochloric acid should be formed in the reaction of hot lava with sea water. A little iron may have been in the colloidal state, or adsorbed by the colloidal silica formed in such a reaction. It is probable that colloidal or adsorbed iron gives to jasper the red or brown color, but this coloring, if due to colloids, could also be formed in other ways.

Attention is called by Van Hise and Leith[40] to the association of basalts and ironstone in Great Britain. These clay-ironstone ores are usually associated with coal beds or vegetable remains.[41] Some of them show that molluscan life flourished on the spot at the time of formation. Geologists generally have not hesitated to connect the origin of these iron ores with the decomposition of rocks by weathering. It is probable, however, that porous, fresh basalts and tuffs on land furnished a considerable portion of the iron by their rapid decomposition, especially in the presence of abundant plant life. Chert does not occur to any extent with clay-ironstone and associated basalt.

Combination of Iron and Silica

A greenalite-like substance has been produced in the laboratory by Van Hise and Leith.[42] They state that silicic acid and a ferrous salt in the absence of air produce no precipitate, but that "ferrous sulphate reacts directly with solutions of silicates of the alkalies," forming a precipitate of silicate matter similar to greenalite.

When the solutions are very dilute silica probably does not exist as alkali silicate, but as colloidal silica. The colloid should not react with ferrous salts in the absence of air to form a ferrous silicate. Soluble magnesium salts, which are plentiful in the ocean, should also be expected to form insoluble silicates with alkali silicates if iron salts did.[43] Yet only 3 to 5 per cent of magnesia are combined with the greenalite. It is probable, therefore, that in dilute solutions the reactions are more complicated than those of simple double decomposition, possibly similar to adsorption.

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[38] *Op. cit.*, p. 516.

[39] Clarke, F. W., *op. cit.*, p. 475.
Cushman, A. S., The effect of water on rock powders, U. S. Dept. Agr., Bur. Chemistry, Bull. 92, 1905, p. 9.

[40] *Op. cit.*, pp. 508-9.

[41] Geikie, A., *op. cit.*, vol. 2, p. 204; vol. 1, p. 181.

[42] *Op. cit.*, p. 521.

POSSIBILITY OF DERIVATION OF IRON AND SILICA BY WEATHERING

Leaching of Rocks

Under certain conditions, on weathering of igneous rocks, iron oxides remain in place as some of the most stable residual constituents. Under other conditions part of the iron is carried away, though this removal may not keep pace with the abstraction of the more soluble constituents of the rocks.[44] Van Hise[45] gives a table on rock decomposition in which the loss of Fe_2O_3 compared with Al_2O_3 as zero varies between 8.78 per cent and 88.84 per cent. In humid regions the loss of iron is much greater than in arid ones.

In tropical countries decomposition of rocks is rapid and extends to great depth, sometimes as deep as 200 to 300 feet.[46] Branner[47] states that in the forest covered portions of Brazil decay is greater than in the parts devoid of dense vegetation. Decomposition, however, is not limited to any particular region. Organic acids are important factors in the decomposition, according to Branner. In many places the laterites probably represent only a small part of the iron from the decomposed rocks. Many analyses show that, under the same conditions of laterization, titanium oxide and alumina are much more stable than iron oxide. These conditions have been described as follows:[48]

1. Alternating wet and dry seasons.[49]
2. Tropical heat with concomitant abundant vegetation.

As to the importance of abundant vegetation there has been some disagreement. Holmes[50] states that organic growth is usually absent where lateritic deposits occur, and implies that organic matter may be unfavorable to their formation. Campbell,[51] however, who probably expresses the opinion of the majority of the investigators, thinks that sterility of the soil sets in due to the formation of a hard crust of iron oxide at the surface when laterization is nearly completed. This oxide is deposited there from iron-bearing ground water reaching the surface. Changes in water table are also a factor. Simpson[52] remarks that "Primary laterite is a true efflorescence" brought to the surface by capillarity.

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[43] Van Hise and Leith, *op. cit.*, p. 521.

[44] Merrill, G. P., Rocks, rock-weathering and soils: New York, 1913, pp. 197-211.
Leith, C. K., and Mead, W. F., Metamorphic geology: New York, 1915, pp. 1-24.
Lang, R., Geologisch-mineralogische Beobachtungen in Indien: Zentralblatt Min., 1914, pp. 257, 513, 545.

[45] Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Surv. Mon., 1904, p. 515.

[46] Derby, O. A., Note on the decay of rocks in Brazil: Am. Jour. Sci., vol. 27, 1884, p. 138.

[47] Branner, J. C., Decomposition of rocks in Brazil: Bull. Geol. Soc. Am., vol. 7, 1896, pp. 255-314.

[48] Maclaren, M., On the origin of certain laterites: Geol. Mag., vol. 43, 1906, pp. 536-47.
Simpson, E. S., Notes on laterite in western Australia: Geol. Mag., vol. 49, 1912, p. 402.

[49] Campbell states that laterites also form in continually wet climate: Econ. Geol., vol. 18, 1923, p. 197.

[50] Holmes, A., The lateritic deposits of Mozambique: Geol. Mag., vol. 51, 1914, pp. 532-33.

[51] Campbell, J. M., Laterite, its origin, structure and minerals: Mining Mag., vol. 17, 7, p. 178.

It seems to the present writer, then, that no hard iron oxide crust could form near the surface, if marked seasonal changes do not exist.[53] This seems to be borne out by the fact that only areas which are relatively small, compared with the great basins of many tropical rivers, are covered by laterite deposits. Most of the iron over the large basins must, therefore, be removed in some form or other by the surface and ground waters, probably with the aid of organic solutions.

Iron and Silica Carried by Waters Rich in Organic Matter

Attention was called to the large amount of silica and iron carried by rivers rich in organic matter (p. 46). The following analyses of the water of the Amazon River and its tributaries have been taken from Katzer[54] and recalculated to parts per million:

TABLE I

ANALYSES OF WATER FROM AMAZON RIVER AND TRIBUTARIES

(Parts per million)

	Amazon[a]	Amazon[b]	Paraná-mirim	Maecuru	Xingu	Tapajos	Itapacurú-mirim
SiO_2	9.4	12.2	8.8	19.2	9.6	9.2	9.0
$Al_2O_3 + Fe_2O_3$	3.6	6.2	9.5	6.6	3.9	2.8	6.8
Organic matter	5.7	8.9	6.3	5.8	11.8	12.2	11.6
Total solids at 110°	39.0	54.5	59.7	52.6	57.2	50.5	64.1
Suspended organic matter	37.2	61.4	100.8	96.7	56.3	62.8	103.2
Suspended inorganic matter	63.2	135.2	111.2	99.6	31.2	28.4	188.4

[a] Amazon River at Obidos at a depth of 26 m.
[b] Amazon River at Obidos at a depth of 0.5 m.

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[52] *Op. cit.*, p. 400.

[53] Lang, R., *op. cit.*, p. 257.

[54] Katzer, F., Grundzüge der Geologie des unteren Amazonasgebietes: Leipzig, 1903, p. 45.

Figures for CaO, MgO, K_2O, and Na_2O have been omitted. Lime is the only constituent which is abundant besides silica and iron. Al_2O_3 and Fe_2O_3 were not separated in the analyses, but there is little doubt that most of the "$Al_2O_3 + Fe_2O_3$" is iron oxide. This appears very probable when these analyses are compared with those of other South American and tropical streams in which iron is almost always greatly in excess over aluminum. These analyses seem to be in accord with experimental evidence of the writer, in which it was shown that iron up to 8.5 parts per million was exceedingly stable in organic solutions. A similar agreement is found between the amount of silica held by the tropical rivers, and that contained in the organic peat solutions of the laboratory.[55]

According to Katzer,[56] the Amazon River normally has a flow of 120,000 cubic meters per second, 200 miles from its mouth. During flood time this volume may increase several fold. If an average of three parts of iron per million is assumed for the water (which would be in keeping with the analyses), the Amazon River in 176,000 years could carry about 2,000,000 million metric tons of iron to the sea—the amount assumed for the Biwabik formation (p. 47). The amount of silica carried would be correspondingly large. If, however, the Biwabik formation extends to the Gogebic Range, as is postulated on a previous page, then it must be assumed that the period of its deposition required a longer time.

In a basin the size of that of the Amazon River, the iron from rock of a thickness of only a few feet would be needed to furnish the stated amount. We may postulate conditions assumed by others[57]—many fresh basalt flows and tuffs on land, possibly with much pyrite like that in the greenstone of the Lake Superior region. Under such conditions enough iron could be dissolved from a much smaller area than the Amazon Basin without there being a decomposition to a greater depth than is common.

Reasons for Favoring Weathering Hypothesis in Case of the Biwabik Formation

The following additional reasons favor the hypothesis that iron and silica were derived from land and transported by rivers rich in organic matter:

1. A steady supply of material over a long period would be assured by such a source.

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[55] Gruner, J. W., Econ. Geol., vol. 17, 1922, pp. 423-46.

[56] *Op. cit.*, p. 38.

[57] Van Hise and Leith, *op. cit.*, pp. 512, 514.

2. No abnormally acid or basic solutions would have been necessary to carry the salts of iron and silica to their places of deposition without suffering premature precipitation.

3. Carbon dioxide, derived from the oxidation of organic matter on the sea floor, could prevent the deposition of calcium and magnesium carbonate to a certain extent by the formation of soluble bicarbonates.

4. The average sedimentary rock contains less magnesia and more lime than the igneous rock from which it is derived.[58] The Biwabik formation contains more magnesia than lime. Experiments dealing with adsorption by organic and inorganic matter seem to show that magnesia is adsorbed more rapidly than, and probably in preference to, lime. Moreover, the fact that iron and magnesium show more tendency to associate, both in sedimentary and igneous rocks, than iron and calcium is shown by the abundance of ferromagnesian minerals especially in old rocks.

5. If we consider rivers rich in organic matter as the transporting agency, it does not seem necessary to account for anything except the lack of lime in the iron formation. There is no reason why calcium and the larger part of magnesium carried to the sea by such rivers could not have been deposited in a different, probably a deeper, part of the ocean. The occurrence of almost pure limestone certainly proves that there has been separation of the constituents of river waters. Moreover, there exists a gradation between iron-bearing formation and calcareous rocks on the Gunflint Range and the east end of the Gogebic Range.[59]

6. The Biwabik and Gunflint formations show no signs of volcanic disturbance, either sudden uplift or sinking of the sea floor during sedimentation. A slow, steady subsidence probably took place. If great volcanic activity had occurred within a hundred miles, some indications might be expected in the structure of the sediments.

7. Lavas were extruded during Keewatin time in greater quantities than during any succeeding period, yet the greatest development of iron-bearing formations occurred during the Upper Huronian. This suggests, at least, that these lavas were the source of iron-bearing sediments not so much during the time of their extrusion, as during their exposure to weathering much later.

8. There exist large iron-bearing formations which are not associated with larger masses of contemporaneous basic igneous rocks. The pre-Cambrian (?) Itabira formation of Minas Geraes, Brazil, is such a primary sediment.[60]

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[58] Leith and Mead, *op. cit.*, p. 84.

[59] Van Hise and Leith, *op. cit.*, p. 515.

[60] Leith, C. K., and Harder, E. C., The hematite ores of Brazil and a comparison with the hematite ores of Lake Superior: Econ. Geol., vol. 6, 1911, p. 670.

DEPOSITION OF IRON AND SILICA

ORIGIN OF OÖLITES AND SIMILAR GRANULES

As much of the iron and silica of the Biwabik iron formation is found in the shape of granules of the size of oölites, their origin becomes one of the chief problems in a study of the deposition of the formation.

Link's[61] experimental work has shown that calcium carbonate, when precipitated as finest mud, will form oölites. Essentially the same thing is reported by Vaughan.[62] Brown[63] comes to the conclusion that oölites are produced either by algae or similar organisms, or chemically by precipitation. The tendency now is to favor more the organic origin of deposits in cases in which it may be either inorganic or organic, since bacterial action and other micro-organic action are now recognized.[64] It is also possible that inorganic and organic formation of oölites can go on side by side, or that organisms cause precipitation of colloids, while the actual shaping of oölites from these colloids is due to the "tendency of the droplets forming during the separation of the dispersed phase of an emulsoid to coalesce," as expressed by Bucher.[65]

The cause of the formation of concentric layers in oölites has been studied by Schade,[66] who comes to the conclusion that in a deposit consisting mostly of colloidal material (gel), the tendency for the formation of concentric rings is less than in a mixture of crystalloids and colloids. Bucher[67] thinks that the rate of formation of the spherulites is important, those forming rapidly being more or less without definite structure. He also says that "the amount of other substance thrown out simultaneously with, and mechanically enmeshed in, the growing structure" has some effect on the structure.

In the Biwabik formation are three kinds of granules:

1. Typical oölites made up of concentric layers. They consist of red jaspery or black graphitic (?) material with a center of the same material or of fine-grained chert. They do not make up one per cent of all the granules. Spurr[68] and Leith[69] have mentioned them.

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[61] Link, G., Die Bildung der Oolithe und Rogensteine: Neues Jahrb., Beilage Bd. 16, 1903, pp. 495-513.

[62] Vaughan, T. W., Remarks on the geology of the Bahama Islands and on the formation of the Floridian and Bahaman oölites: Jour. Wash. Acad. Sci., vol. 3, 1914, pp. 302-4.

[63] Brown, T. C., Origin of oölites and the oölitic texture in rocks: Bull. Geol. Soc. Am., vol. 25, 1914, p. 772.

[64] See, for example: Drew, G. H., Papers from the Tortugas Laboratory, Carnegie Institution, Washington, vol. 5, 1914, p. 44.

Wethered, E. B., The formation of oölite: Quart. Jour. Geol. Soc., vol. 51, 1895, p. 205.

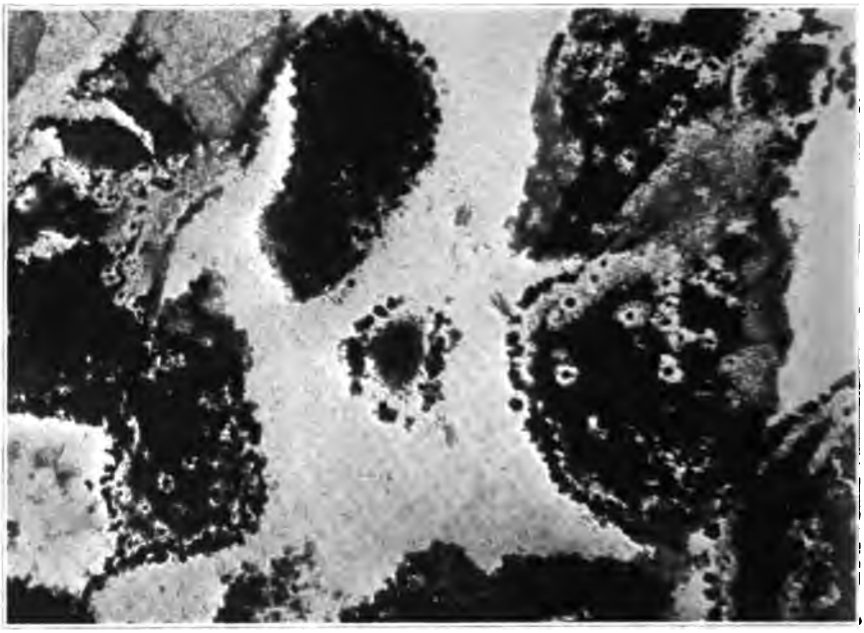
[65] Bucher, W. H., On oölites and spherulites: Jour. Geol., vol. 26, 1918, p. 594.

[66] Schade, H., Zur Enstehung der Harnsteine und ähnlicher konzentrisch geschichteter Steine organischen und anorganischen Ursprungs: Zeitschr. Chem. u. Ind. d. Kolloide, vol. 4, 1909, pp. 175-80, 261-66.

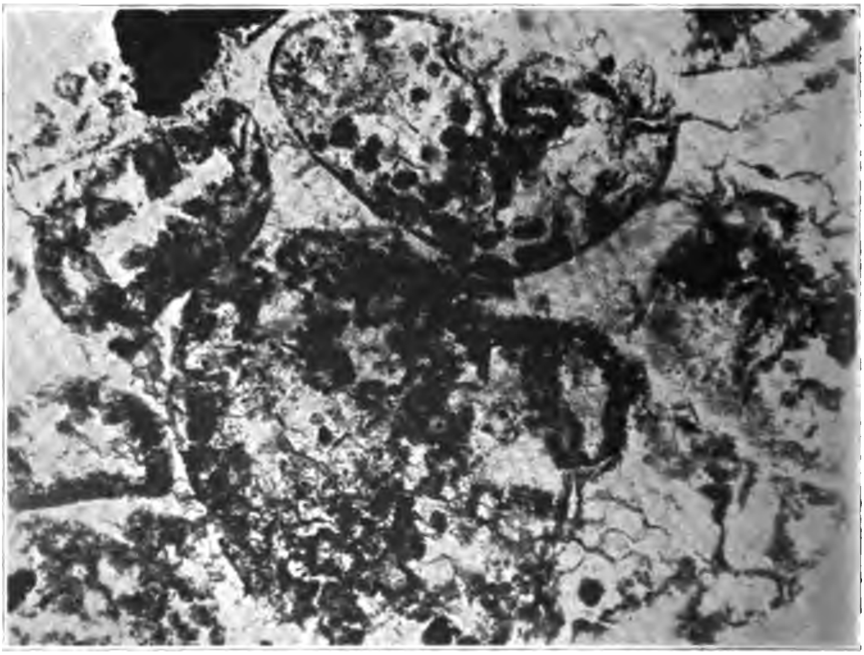
[67] *Op. cit.*, p. 594.

[68] *Op. cit.*, Pl. VII, Fig. 2.

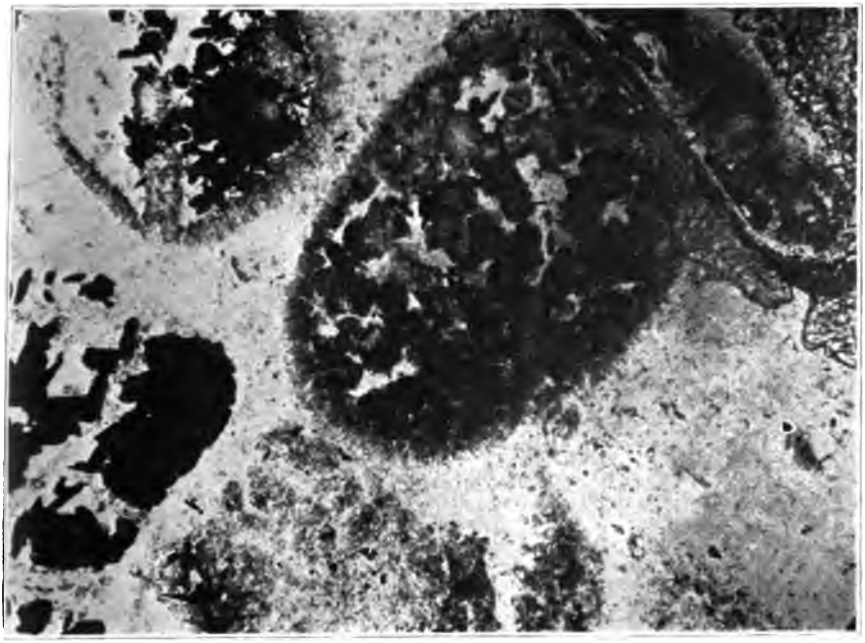
[69] Op. cit., Pl. XIII.



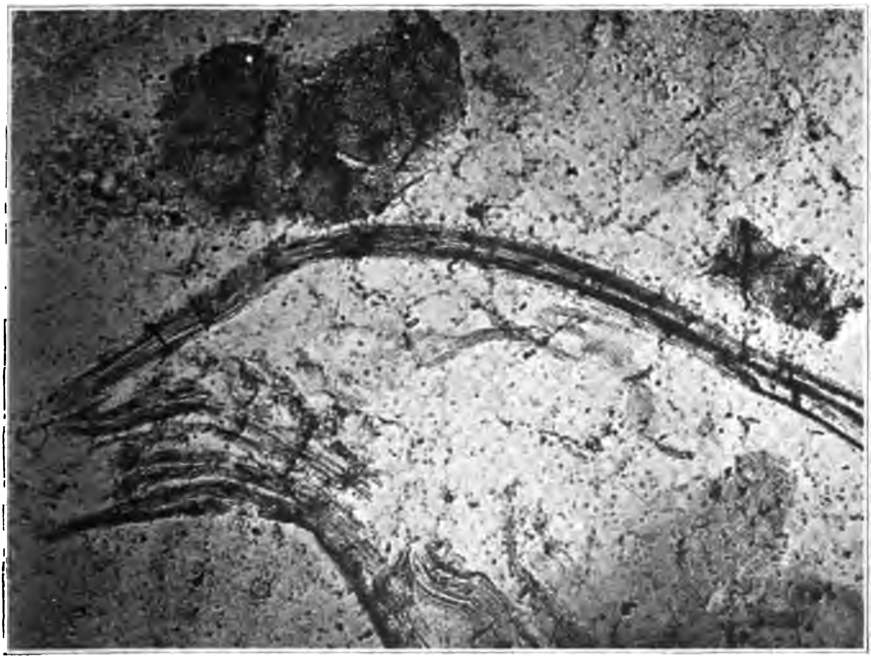
A. GROUPS AND CHAINS OF MINUTE CONCENTRIC RINGS OF CHERT IN GRANULES OF GREENALITE. MATRIX OF LARGE GRANULES IS CHERT. NUCLEI IN SMALL RINGS AND SURROUNDING MATRIX OF GREENALITE-LIKE SUBSTANCE. SOME RING STRUCTURES NOT VISIBLE. x 88



B. STRUCTURES SIMILAR TO A. CHERT RINGS SURROUNDED BY "DUSTY" BLACK RINGS. NUCLEI OF SAME MATERIAL. SOME ROUND DUSTY BLACK AREAS WITHOUT RINGS. COMPARE WITH PLATE XI, B. x 88



C. LARGE GRANULES (IN MATRIX OF CHERT) WITH SMALL CONCENTRIC STRUCTURES OF HEMATITE "DUST" AND CHERT. HEAVY BLACK AREAS ARE MAGNETITE AND HEMATITE. NEEDLES OF SPECULAR HEMATITE CUT THE CONCENTRIC STRUCTURES. COMPARE WITH PLATE XI, B. x 165



D. PART OF STRUCTURE IN FIGURE 16. FROM "ALGAL STRUCTURE" HORIZON OF GUNFLINT RANGE. DARK AREAS IN PICTURE ARE LIGHT GREEN. X 220

2. Typical greenalite granules and their alteration products. No internal structure is visible in these "oölites." Their alteration products are many times more abundant than the unaltered granules, and at many places cannot be distinguished from the alteration product of the kind of structure described under (3).

3. Bodies which have the size and outlines of greenalite granules, but which possess a visible internal structure. They appear to be made up of groups of chains of minute concentric rings which are commonly of chert but may be of a dark graphitic (?) dust or exceedingly minute specks of hematite. Their centers and the matrix in which these rings are embedded are practically always of the same material, but different from the rings themselves. For example, Plate X, A shows chert rings with greenalite centers and matrix. Black centers (probably not magnetite) with a white chert ring and another "dusty" black one around it may be seen in Plate X, B. A somewhat similar structure is that of Plate X, C. In it the dark centers are missing. Spurr[70] noticed these structures and has an excellent illustration of the greenalite phase of them in his report. He thought that they represented a decomposition phase of "glauconite." Leith[71] also illustrates them and says that they suggest organic structures. In the Clinton ores in which similar structures occur, they are "clearly due to the replacement of a shell with regular structure," according to Leith. Wethered[72] shows some similar structures in oölitic limestone, and attributes them to organisms.

Moore[73] also observed similar structures in the granules of the iron formation of the Belcher Islands. These are of remarkably uniform size (0.03-0.04 mm.). Due to the difference in degree of alteration, they may be composed of different minerals as in the larger greenalite structures. The fact that they are preserved only in fine-grained or almost amorphous material, and not in the more crystallized granules, indicates the primary origin of these structures. It is usual to find them penetrated by magnetite, hematite, or amphibole crystals. In places they may form rings around apparently massive greenalite. When such greenalite granules were examined carefully with strong artificial light, it was sometimes noticed that the apparently homogeneous mass showed faint outlines of these minute structures.

About 200 thin sections from the Biwabik and Gunflint ranges were examined; in many of the less altered ones these structures were seen.

[70] *Op. cit.*, Pl. VI, Figs. 1, 2.

[71] Mon. 43, p. 117 and Pl. XIV, A, B.

[72] *Op. cit.*, Figs. 5, 7.

[73] Moore, E. S., The iron formation on Belcher Islands, Hudson Bay, etc.: Jour. Geol., vol. 24, 1918, pp. 412-38.

In most of them (except those from the East Mesabi) at least traces of the structures were preserved. In the light of the other evidence presented on page 57, they are attributed to the work of micro-organisms, and may be called cell structures. Unless all of the greenalite granules are made up of cell structures or some other form of organism, we may conclude that the following conditions probably would be favorable for the formation of granules without internal structure:

1. Relatively rapid deposition of colloidal precipitates.
2. Lack of strong tendency to crystallize, on account of the colloidal character of silica and ferrous and ferric organic compounds and hydroxides.
3. Absence of fragmental grains which could have formed the nuclei of oölites.

STRUCTURES RELATED TO GREENALITE GRANULES

Many iron ore formations show granular structures similar to greenalite, but most of them differ in one respect—that the majority of their granules are true oölites with concentric ring structures. In most of the formations, however, there occur a relatively small number of granules which have not concentric structures, and therefore resemble typical greenalite structures.

In the Wabana oölites[74] other features also are noteworthy. Boring algae have been found in the oölites, and Hayes thinks it possible that they were active in the production of hematite.

In the Biwabik formation we find hematite- and greenalite-like minerals together. Hematite is commonly taken to be an alteration product of the greenalite. In the Wabana oölites hematite and chamosite occur in alternating concentric rings. It seems fairly certain that such hematite is not an alteration product of chamosite. It would be difficult to believe that one concentric layer could have remained in one state of oxidation while adjacent ones were changed to some other state, unless there was a conspicuous original difference. Ferrous silicate and ferric oxide (hydroxide), both primary according to Smith,[75] also occur in the Clinton ores. There is no reason, then, why a *ferric* oxide, where associated with greenalite, could not have been an important primary mineral in the Biwabik formation.

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[74] Hayes, A. C., Wabana iron ore of Newfoundland: Canada Geol. Surv. Memoir 78, 1915.

[75] Smith, C. H., Jr., On the genetic significance of ferrous silicate associated with the Clinton iron ores: University of State of New York, Albany, 1919, p. 190.

The similarity in shape of the greenalite and Clinton granules has been emphasized by Leith.[76] McCallie[77] describes Clinton ore granules with a nucleus of a greenish mineral which he thinks is similar to greenalite.

Glauconite resembles greenalite closely in shape and internal structure. Spurr[78] thought that greenalite is a potassium-poor variety of glauconite. Leith objected[79] to this, because aluminum is also absent from the greenalite, and because detrital mud, always associated with glauconite, is not found with greenalite. It is probable, however, that greenalite granules form by processes similar to those active in the making of glauconite. According to Clarke,[80] this process may be adsorption. So far, however, no generally accepted theory has been advanced for the formation of glauconite.[81]

MICRO-ORGANISMS IN AND NEAR THE BIWABIK FORMATION

Lower organisms seem to have been widespread as early as Archean time.[82] Their presence in pebbles at the base of the Pokegama quartzite and in chert which fills cracks in the conglomerate has been described on page 6. Fossiliferous chert of the same kind also fills joint cracks and irregular areas in the underlying graywacke and greenstone. It is thought that this chert filling the joint cracks and areas is at least as old as the bottom beds of the Biwabik formation.[83]

The majority of the thin sections of the chert show structures which resemble organic structures. These structures, however, may often be only faintly outlined. Plates XI and XII show iron bacteria, blue-green algae, and bacilli. Plate XIII pictures similar algae. Figures 14 and 15 are other organic structures. All of them are found in the same kind of chert though in different specimens and places. They show that life was abundant in the sea in which the cherts were deposited.

In studying the algae of Plate XI, B and C, and the organisms shown in Plates III and IV and in Figures 14 and 15, and comparing them with the peculiar structures of Plate V, which show a faint resemblance in places to some irregular greenalite granules, it is observed that there seems to exist a gradation from the perfect algae of Plate XI (which form a network) to groups which seem to consist only of concentric rings, or round spots (like some in Plate XI, B) without any connecting portions or sheaths between them. These simpler rings or spots usually seem to be a little larger than the cross sections of the algae in Plate XI, C. They resemble the rings in the greenalite structures (Pl. X, A, B, and C) very much, and strongly suggest a relation in origin.

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[76] Mon. 43, p. 251.

[77] McCallie, S. W., Report on the fossil iron ores of Georgia: Geol. Surv. Georgia, Bull. 17, 1908, p. 174.

[78] *Op. cit.*, p. 242.

Hummel, K., Die Entstehung eisenreicher Gesteine durch Halmyrolyse: Geol. Rundschau, vol. 13, 1922, pp. 49-77; Review in Econ. Geol., vol. 18, 1923, p. 612.

[79] *Op. cit.*, pp. 242, 254.

[80] *Op. cit.*, pp. 513-14.

[81] Murray J., and Renard, A. F., Voyage of the challenger; deep sea deposits: 1891, p. 389.

Murray, J., and Hjort, J., Depths of the ocean: London, 1912, p. 189.

Collet, L. W., and Lee, G. W., Recherches sur la galuconie: Proc. Roy. Soc. Edinburgh, vol. 26, 1906, pp. 259-62.

Andree, K., Uber Sedimentbildung am Meeresboden: Geol. Rundschau, vol. 8, 1917, pp. 59-61.

[82] Gruner, J. W., Algae, believed to be Archean: Jour. Geol., vol. 31, 1923, p. 146.

[83] Gruner, J. W., Econ. Geol., vol. 17, p. 418.

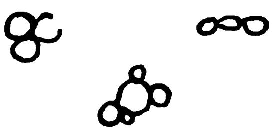

FIGURE 14. SKETCH OF ORGANIC STRUCTURES REPLACED BY SILICA OR LIMONITE. X 100. SLIDE M 932

New organisms were also found in the cherts of the algal structure horizon of the Gunflint and Biwabik formations. Bacilli (there is little doubt that they are such) of the same kind as those shown in Plate XII, B were found in two specimens from the algal structures of the Upper Cherty division near Hibbing. They are of the same shape and size as those in Plate XII, B, but are less numerous.

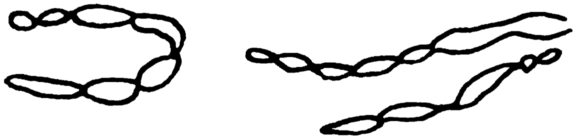

FIGURE 15. SKETCH OF RING AND CHAIN STRUCTURES OF BROWNISH OR GREENISH MATERIAL. X 150. SLIDES M 943 a, M 944 b, M 947 a

In this connection may be mentioned rods of silica (about 10 to 12 microns long) which were observed by Bleicher[84] in oölites of the Minette ores of France. These rods are said to resemble bacteria. In a specimen from the algal structure horizon of the Upper Cherty division on the Gunflint Range, the algae shown in Figure 16 and in Plate X, D were

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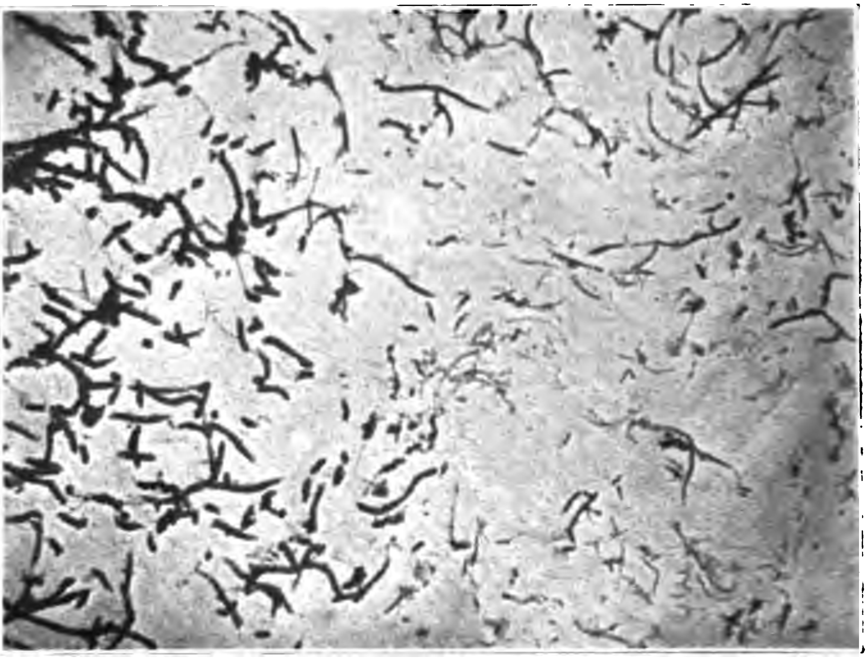
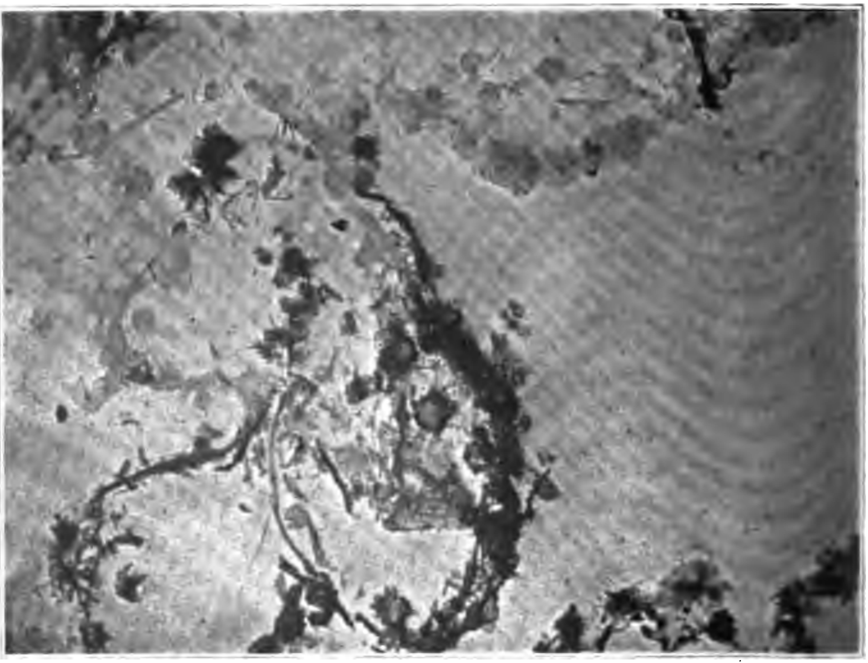
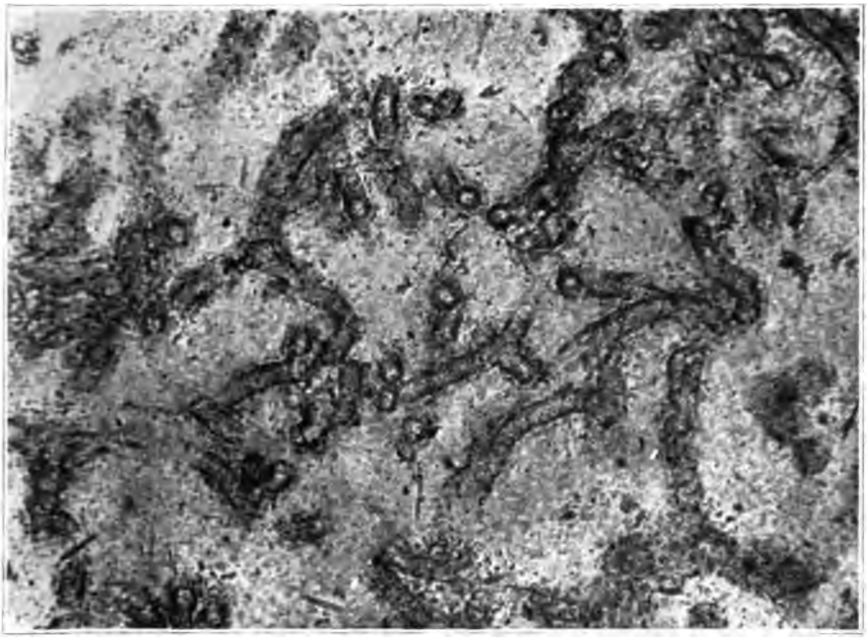
[84] Quoted by Van Werweke, L., Bemerkungen über die Zusammensetzung und die Enstehung der lothringisch-luxemburgischen oolithischen Eisenerze: Zeitschr. prak. Geol., vol. 9, 1901, p. 396.



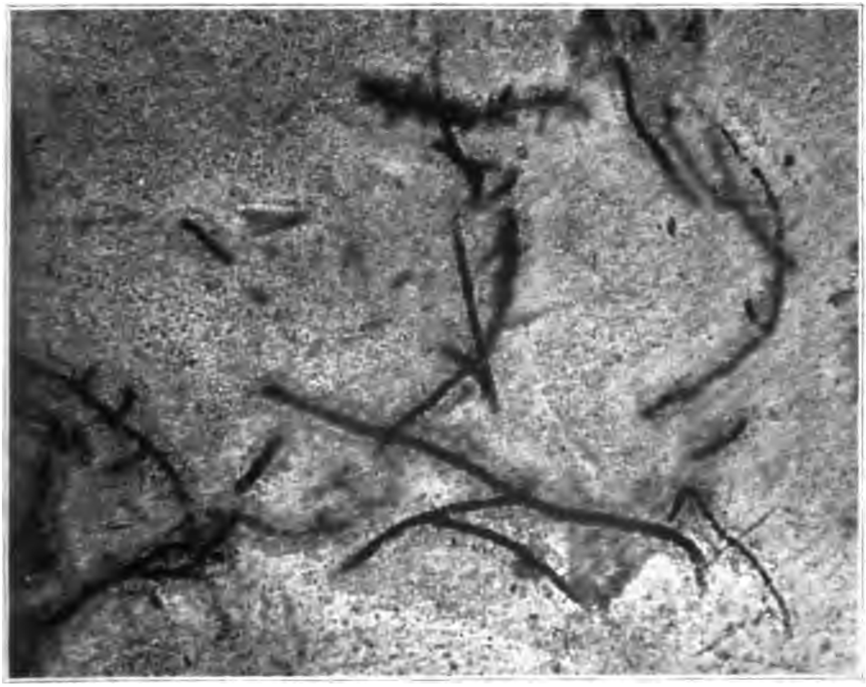
A. IRON BACTERIA AND ALGAE IN CHERT. MOST BACTERIA OUTLINED BY HEAVY SHEATHS OF BROWN COLOR. X 77



B. ANOTHER VIEW OF A. ALGAE ARE PROMINENT. NOTE RESEMBLANCE OF ROUND STRUCTURES TO THOSE IN GREENALITE STRUCTURES. PLATE X DARK COLORED STRUCTURES ARE BROWN. x 88



C. ALGAE RESEMBLING MICROCOLEUS (PROF. JOSEPHINE TILDEN) IN CHERT. SAME SLIDE AS A. CHERT AND ALGAE ARE PRACTICALLY OF THE SAME COLOR. x 340



D. IRON BACTERIA RESEMBLING CHLAMYDOTHRIX FROM SAME SPECIMEN AS ALGAE IN C. x 340

found. There still exists some doubt as to whether these plants belong to a higher class than algae.[85]

CHEMICAL AND ORGANIC PRECIPITATION

It was pointed out on page 46 that iron can be taken into solution in several ways, but that it is precipitated too rapidly to be transported long distances. However, in solutions containing small amounts of organic matter, iron is not precipitated completely by inorganic agencies. Silica is also very stable in solutions containing organic matter and it seems that it cannot be precipitated completely by ordinary inorganic means from such solutions.

The existence of iron bacteria and algae at the time of deposition of, and in, the Biwabik formation makes considerable organic precipitation highly probable. Drew[86] has shown the importance of bacilli in organic precipitation of limestone. Algae, radiolaria, and diatoms cause the deposition of silica. Iron bacteria, as shown by Harder, are some of the most efficient precipitating agents of iron. According to him[87] and to Ellis,[88] all traces of iron bacteria may easily become altered beyond recognition. Mumford[89] believes that a certain type of bacillus can precipitate iron under anaerobic conditions, when some of the precipitate will become partially reduced to the ferrous state (not sulphide). If this is the case, it might offer an explanation for the occurrence of a part of the ferrous iron. Though iron bacteria of the higher type have not been found in sea water, this does not preclude their existence there. Neither are we sure that the Biwabik formation was deposited in sea water.

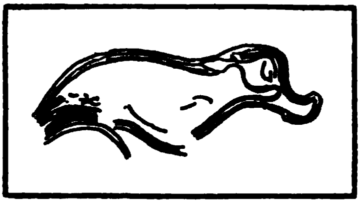


FIGURE 16. TRACING OF AN ORGANIC STRUCTURE FROM THE ALGAL STRUCTURES OF THE UPPER CHERTY IN THE GUNFLINT FORMATION. X 80. SLIDE M 561
A PORTION OF THIS ORGANISM IS SHOWN IN PLATE X, D

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[85] The writer wishes to express his thanks to Dr. C. D. Walcott and to Dr. Albert Mann, of the Smithsonian Institute, for examining one of the sections containing fungi-like plants, to Professor Josephine Tilden, Professor C. O. Rosendahl, and Professor F. K. Butters, of the Department of Botany of the University of Minnesota, for the identification of algae and similar structures, and to Professor A. T. Henrici, of the Department of Bacteriology, for identification of the bacteria. Professor Charles Schuchert, of Yale University, also had the kindness to examine the photographs.

[86] *Op. cit.*

[87] *Op. cit.*, p. 80.

[88] Ellis, D., Iron bacteria: London, 1919, p. 169.

[89] Mumford, E. M., A new iron bacterium: Chem. Soc. Jour., vol. 103, 1913, p. 650.

Bacterial action, however, does not mean that inorganic processes did not take part in the precipitation of iron and silica. Temporary conditions may be imagined under which algae and bacteria could not thrive.

Special conditions are required for the separation of mechanical sediments from chemically dissolved or colloidal matter. This separation must depend on physiographic conditions similar to those for the formation of glauconite of which Murray and Renard[90] say that it is found "most characteristically on the continental slopes of high and bold coasts where currents from different sources alternate with the season."

ALTERATIONS OF ORIGINAL SEDIMENT

Grout and Broderick[91] have emphasized certain changes of oxidation, re-solution, and mechanical action which probably took place during deposition. This is illustrated by Figure 17, where a hard slaty layer has buckled and broken in several places. Such breaking may have given rise to intraformational conglomerate. Figure 2 seems to prove that solution went on at the surface of carbonate precipitates, producing the stylolitic surface upon which slate was laid down. Probably most of the organic matter in the precipitates, while still at, or near, the surface, was oxidized to carbon dioxide. This could have caused local re-solution of iron which was then redeposited under different conditions. Such a process may have led to the formation of irregular bands of iron oxides and carbonate, which do not seem at all related to original sedimentation. Many other reactions probably occurred at that time, and some concretions developed.

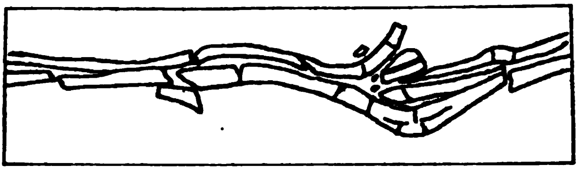

FIGURE 17. SKETCH SHOWING DEFORMATION AND BREAKING OF A DENSE SLATELIKE LAYER

Amphiboles and magnetite were formed, on deep burial of the formation. The ferruginous cherts are the result of this metamorphism. Lately the statement has been made that magnetite in minute dust particles may form as a colloid on the sea bottom.[92] If this actually happens, it probably is on such a small scale that it would not enter seriously into any discussion of the origin of the magnetites of the Mesabi Range.

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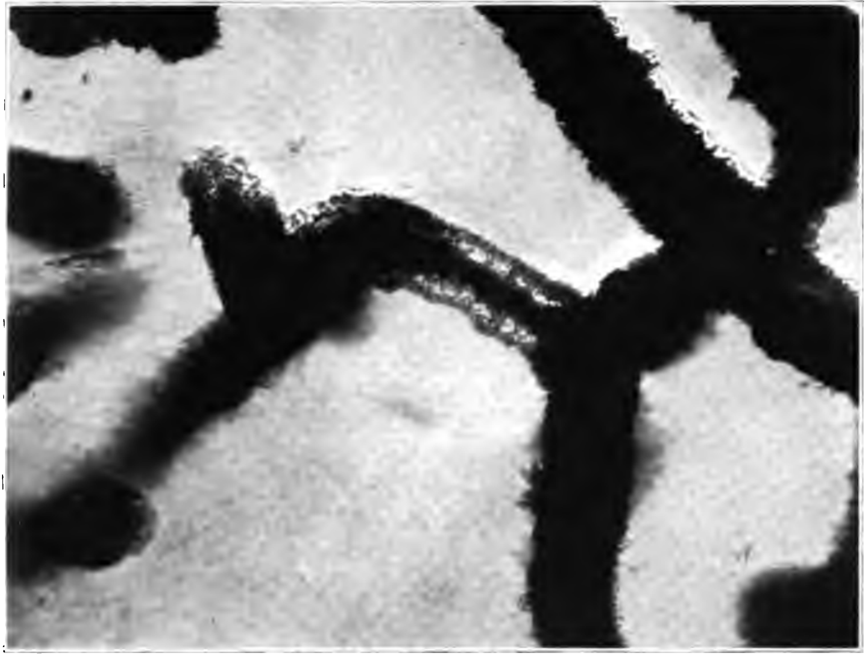
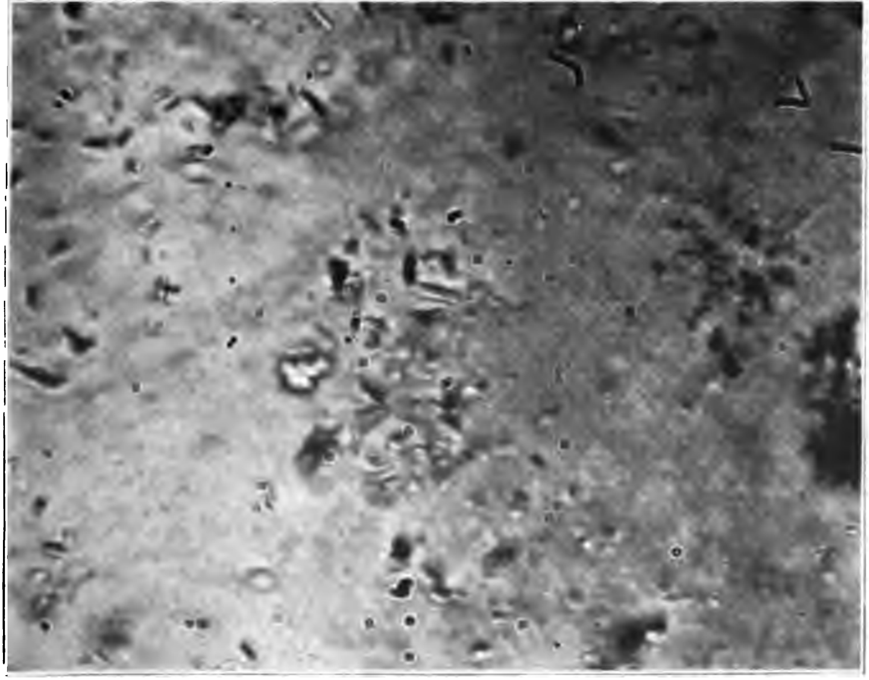
[90] *Op. cit.*, p. 234.
[91] *Op. cit.*, Bull. 17, p. 42.
[92] Berz, K. C., Ueber Magneteisen in Marinen Ablagerungen: Centralbl. Min., 1922, pp. 569-77.

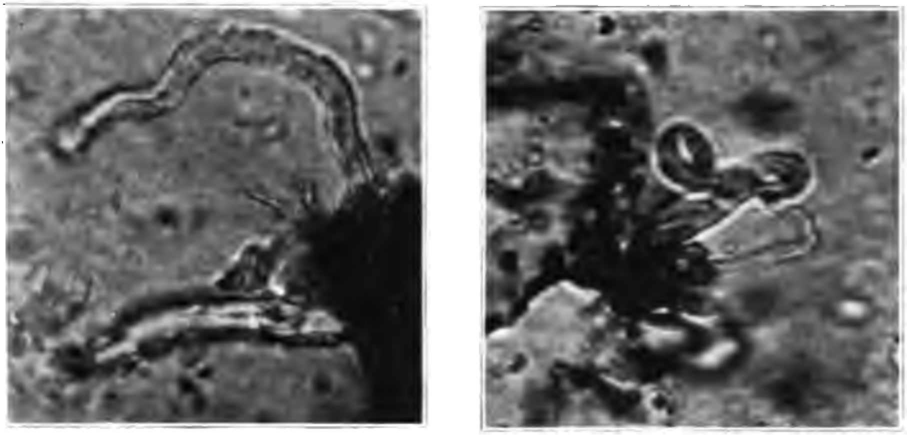


A. IRON BACTERIA FROM SAME SPECIMEN AS PLATE XI. NOTE SHEATH AND CROSS SECTION OF SHEATH IN UPPER RIGHT CORNER. BLACK AREAS BROWN IN SPECIMEN. X 1540

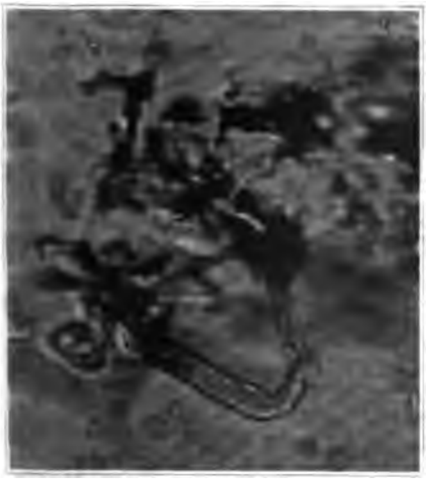


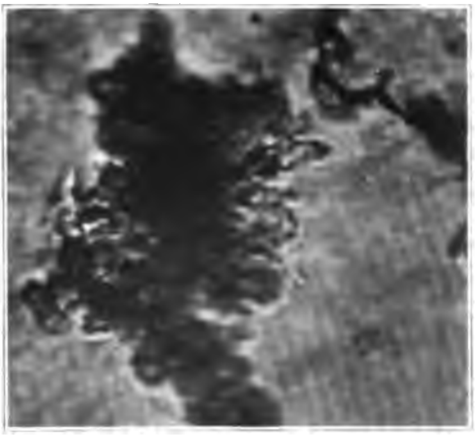
B. BACILLI FROM THE SAME SPECIMEN AS A. MINUTE RODS ROUNDED AT THE ENDS; SOME ARE BENT; UNIFORM IN SIZE AND NUMBERS. ONLY A FEW CAN BE GOT INTO FOCUS AT ONE TIME. THEY ARE WHITE LIKE THE CHERT. X 1540

PLATE XIII



A, B, AND C SHOW SEVERAL TRICHOMES GROWING FROM A COMMON CENTER





D. IN THIS PHOTOGRAPH THE TRICHOMES ARE SO NUMEROUS THAT THEY APPEAR TO BE ONE MASS

BLUE-GREEN ALGAE RESEMBLING INACTIS AND MICROLEUS IN CHERT. THE TRICHOMES (THREADS) REPRESENT THE REAL PLANTS WHICH LIVE IN THE SECRETED SHEATHS SIMILAR TO THOSE SHOWN IN PLATE XI C. x 2200. SLIDE M 931 b

CONCLUSIONS

From the foregoing discussions, the following conclusions may be reached: During Upper Huronian time there existed large land areas in North America which were covered largely with greenstone and basalts. It is probable that fresh extrusive rocks and volcanic tuff and ash were deposited on parts of the land as well as in the sea basins then existing. The climate of the continent was humid. Vegetation of a low form was abundant, and aided in the rapid decay of the rocks. Under these conditions iron, which usually is one of the most stable elements in weathering, went into solution to a large extent, but only in waters with organic colloids was it stable for any length of time in the zone of oxidation. Silica was also dissolved on a large scale. Both iron and silica were carried to the sea by rivers rich in organic matter.

Whether this was a large inland sea or the ocean is a matter of speculation. There is little to indicate that the iron-bearing cherts could not have been precipitated in fresh water. The suspended material carried by the rivers was deposited probably in deltas, while the stable colloids of iron and silica were carried by currents to places of shallow and clear water. Only under exceptional conditions did mechanically suspended material reach these places and become deposited as slate. Such exceptional conditions may have been unusually large floods, and temporary changes in the coast lines.

The precipitation of silica, iron, and part of the organic colloids was caused chiefly by algae and bacteria, which used the organic matter for their life-processes and the inorganic silica or iron for the building of their cells or sheaths. It is also probable that inorganic reactions caused much colloidal silica, iron, and organic matter to be precipitated. By adsorption some of these colloids partly united to form indefinite amorphous iron silicates. These may have been ferrous silicates from the beginning, or may have been ferric at first. Iron hydroxides and silica probably did not form silicates at many places. One reason may have been that the iron was not of the proper valence or in condition to make a silicate.

A large part of the colloidal precipitates assumed the shapes of oölites, differing, however, from typical ones in their internal structure. In many places the granules thus formed seem to be made up of groups of cells; this suggests algae or similar plants. It is thought improbable that all of the granules showing oölitic shape were deposited originally as ferrous silicate. A large portion of them probably consisted of iron oxides, cherts, or carbonates.

A part of the silica contained in the taconite may have been contributed to the sea directly by magmatic springs or hot submarine lava flows. We do not believe, however, that much iron had this origin.

Before a freshly precipitated layer of iron-bearing formation could be buried to any depth, there was considerable alteration of the amorphous material. Re-solution and diffusion in one place and redeposition in another were accompanied by reduction and oxidation of portions of the iron. Most of the organic matter was oxidized to carbon dioxide at this time. On deeper burial, ferruginous chert (taconite) originated by the formation of magnetite, amphiboles, and coarse-grained carbonates from the amorphous minerals and substances.

CHAPTER VIII

THE ORIGIN OF THE HEMATITE-LIMONITE ORE BODIES

The problem of the origin of the ore bodies has been discussed at length by Winchell, Spurr, Van Hise, Leith, and Wolff. In the present report nothing essentially new on this subject is offered. However, some known factors which have a bearing on the origin of the ores may be summarized here.

1. *Structural factors.*—In the previous literature concentration of ore at its present places is supposed to be due chiefly to structural features of the iron formation.

Wolff,[1] who probably expresses the opinion of most geologists, says:

> . . . in every case where the exploration data is complete enough, it has been found that the ore bodies occur where the whole formation has been warped. In the eastern part of the district (Virginia and eastward) the ore bodies are on the crests of gentle anticlines or on axes of combined anticline and syncline. . . . In the central part of the range great broad flexures rather than merely localized ones seem to have determined the locations of the ore bodies. The formation was generally cracked up and the broad structural basins directed the flow of underground waters.

In the present investigation attempts were made to relate ore bodies to original structures of the Biwabik formation. Contour maps and cross sections of the top of the Pokegama quartzite were made to locate any synclines or anticlines. In a few cases the contours seem to show that ore bodies are on anticlines, but about as many are on synclines or even on the limbs of the anticlines.

Field work in the open pits and outcrops is inconclusive on account of the usual slump of the taconite toward the ore bodies. This makes the original structures appear synclinal. There are, however, at least two known examples, the Alpena and Biwabik mines, in which the ore bodies are related to special major structures, a monocline and a normal fault respectively.

Stress has been laid on the importance of impervious layers of the iron-bearing formation in guiding the course of solutions which leached the silica. There is no doubt that this factor is important. An impervious layer, the Intermediate Slate, extends throughout the formation. Great deposits of ore are found above and below it. Along the dip this layer must have been of great importance in the guiding of the leaching solutions. Along the strike, however, it is not so evident that this layer determined the position of ore bodies. The same is true of the Pokegama quartzite which acted as an impervious layer even more than the Intermediate Slate. It was just pointed out, however, that the ore bodies do not seem to be situated upon any particular anticlines or synclines of the Pokegama quartzite.

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[1] *Op. cit.*, pp. 247-49.

How extensive the fissuring and jointing of the taconite was in the places now occupied by the ore bodies is a matter of speculation. It has been thought that the taconite was more fractured in these places than in the rest of the formation. Observations on the natural outcrops of the whole Biwabik and Gunflint formations show that the taconite is extensively fractured throughout, sufficiently so that solutions could have circulated in it with ease almost anywhere.

2. *Textural factors.*—In the description of the various phases of the taconite, page 10, the difference in their textures and the manner of their alteration to ore was given. On account of this difference some beds were undoubtedly much more susceptible to weathering than others. In the cherty phases of taconite a fine grained sandy material forms at first in the process of decomposition. It is due to the disintegration to such sandy material that washing of the ore on the West Mesabi Range is so successful. The formation of this sandy, friable phase seems to be always an intermediate step in the alteration of taconite to completely leached ore, though not so conspicuous in the central and eastern parts of the range because here it exists usually only at the margins of the ore bodies. It has been removed from the bulk of the ore.

The matrix which originally cemented the sandy alteration phase was probably silica, but there is a possibility that there was more carbonate in the matrix of the taconite now weathered than in that which remained unattacked. Considerable attention was paid to such a possibility, but, due to the nature of the problem, no conclusive results were obtained. It was observed, however, that originally very fine grained, dense phases of slaty taconite containing considerable amounts of carbonate weather to a fine grained, porous product not unlike the ore from the cherty phases except in size of grain.

It is a well-known fact that chalcedony dissolves more easily than quartz. Chert,[2] on the other hand, seems to be attacked more easily than chalcedony by weathering. Observations in the field showed that chert pebbles and chert cementing the conglomerate of the Pokegama quartzite were attacked commonly much more than chalcedony pebbles in the same conglomerate. The chert most "worm-eaten," or decomposed, invariably seemed to be that which most closely resembled the chert in which fossil organisms were found. How rapid this decomposition can be is shown by the finding of porous, cellular chert on glaciated surfaces where decomposition probably occurred after the retreat of the continental glaciers. The writer therefore believes that organic chert breaks down more easily than silica precipitated by inorganic agents, provided recrystallization has not advanced very far. The reason for more rapid recrystallization of some cherts than of others is not apparent. That it has taken place at different rates can, however, be observed in many localities.

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[2] In this paper chert may be defined as silica precipitated by organic or inorganic agencies in open bodies of water. The term chalcedony is used for silica deposited in veins and cavities by ground water.

3. *Chemical factors.*—The nature of the chemical factors which caused the formation of ore bodies in some places and not in others is not known, but since structural factors and textural ones alone do not seem to account entirely for the positions of the ore bodies, chemical causes must be taken into consideration. It is not probable, however, that the taconite, altered to ore, was very different in chemical composition from the remaining taconite. It may have contained a little more carbonate and possibly a little more organic matter than the unweathered taconite, but as a whole there cannot have been much difference between the phases of taconite. This is shown by the martite[3] in the ore which is about as abundant as magnetite in the taconite.

It has been assumed by most of the previous investigators that alkaline carbonate waters and oxygen brought about the weathering of taconite to ore. This is probably true. Acid waters would not have attacked the silica more than the iron. Meteoric alkaline waters are abundant, but there is no other instance known in which weathering as complete as that of the taconite to ore has been carried to such depths except in other pre-Cambrian formations. Ordinary laterization rarely is complete at a depth of more than 40 feet, though in this process silicate rocks much more easily attacked are weathered. Conditions of weathering, therefore, must be assumed to have been somewhat different from those known to us today. If the climate had been humid it seems that oxidation would hardly have reached to such depth below the ground water level. The change from magnetite to martite must be extremely slow for microscopic examination of taconite from glaciated outcrops in the Virginia Horn has shown that the magnetite in it has not been changed noticeably by weathering, not even to the depth of a fraction of one millimeter. The taconite of these outcrops has probably been exposed without a cover of glacial drift or soil for centuries.

It seems, then, that the problem of the enrichment of the ore deposits is only partially solved. Conditions and factors in the iron formations of the Lake Superior region, even in one single formation, are so varied that it is difficult to place the emphasis on any particular set of conditions and factors without being in serious disagreement with other investigations.

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[3] Gruner, J. W., *op. cit.*, Econ. Geol., vol. 17, 1922, p. 1.

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2 Sheets 11-30-95

FRONTISPIECE. FALLS OF THE MANITOU RIVER

The University of Minnesota

MINNESOTA GEOLOGICAL SURVEY
William H. Emmons, Director

BULLETIN NO. 20

A GUIDEBOOK TO MINNESOTA TRUNK HIGHWAY NO. 1

BY

G. M. SCHWARTZ

MINNEAPOLIS
The University of Minnesota
1925

PREFACE

This paper is a description of the chief geologic features that may be seen along Highway No. 1 of Minnesota. This highway begins at the Iowa state line south of Albert Lea, and passes northward through the Twin Cities to Duluth and thence extends along the north shore of Lake Superior to the Pigeon River near Port Arthur, Ontario. The report includes thirteen maps which show the locations of roads, towns, and villages, and most of the rocks and land forms that are described in the text. Essentially all places mentioned in the text are located on one of the maps. The work was in charge of Dr. G. M. Schwartz who traversed the entire route and prepared the text. Numerous earlier reports by the Geological Survey of Minnesota and the United States Geological Survey were drawn upon for data and these are appropriately acknowledged in the text. A section on trees and plants is supplied by Dr. C. O. Rosendahl and Dr. F. K. Butters, of the University of Minnesota, and one on fish and game by Mr. Thaddeus Surber.

The paper is intended for the use of the traveler and the general public and as far as practicable highly technical terms are avoided.

This survey has issued a number of other publications treating the geology, surface formations and agricultural conditions, iron ores, manganiferous ores, clays, building stones, peat, etc. These are sold by the librarian of the University of Minnesota at nominal prices. A list of publications of the survey may be had free on application to the librarian of the University or the director of the State Geological Survey.

William H. Emmons

Additional copies of this publication may be obtained from the Librarian, University of Minnesota, Minneapolis, Minnesota.

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CHAPTER I

INTRODUCTION

Few states show a greater variety in natural features than Minnesota. The southwestern portion presents large expanses of almost unbroken fertile prairie; the southeast a much dissected area typical of regions farther south where the glacier has not leveled off the topography resulting from stream erosion. A typical glacial moraine topography characterizes the region around Minneapolis and St. Paul. The northern part of the state presents a much more rugged country famous for its iron mines, and of interest to the tourist because of the great areas of wild and wooded country and its lakes, so numerous that it has been well named, the "Land of Ten Thousand Lakes." The lakes, forest, and delightful summer climate have combined to make the state the goal of thousands of tourists from nearly every state in the Union.

Highway No. 1 is well located to give the traveler a comprehensive view of the various types of Minnesota country. The highway begins at the Iowa state line south of Albert Lea, pursues a northerly course through the Twin Cities to Duluth, thence northeasterly along the north shore of Lake Superior over the new scenic highway 170 miles to the Canadian boundary at the Pigeon River. (See Figure 1.) From there a road continues to Port Arthur and Fort William in Canada. The total length of the highway is nearly 450 miles. The road is kept in good condition over its entire length and much of it is of new construction. Over 100 miles are paved and the remainder is graveled. Within a few years it is planned to pave the entire distance from Albert Lea to Duluth. The route is carefully marked by the Minnesota Highway Department which has charge of all state roads.

FIELD WORK AND ACKNOWLEDGMENTS

The entire length of the route was covered by the writer during the summer of 1924, to gather data for this guide. Information has also been drawn from other sources and the writer is much indebted to the various workers whose results have been utilized. The publications of the Minnesota Geological Survey and the United States Geological Survey have been of particular value, especially the *Final Report of the Geological and Natural History Survey of Minnesota,* by N. H. Winchell, and Bulletins 13 and 14 of the Minnesota Survey, by Leverett and Sardeson. The series of guidebooks of the United States Geological Survey have contributed much material. The publications of the Minnesota Historical Society were of great value, especially *Minnesota Geographic Names,* by

Warren Upham. Acknowledgments for much assistance are due to Mr. Solon J. Buck, superintendent of the society. Credit for the chapter on fish and game is due to Mr. Thaddeus Surber, of the Minnesota Game and Fish Department. Dr. Otto Rosendahl and Dr. Frederic K. Butters, of the Botany Department of the University of Minnesota, contributed the chapter on trees and plants. The Minnesota Highway Department furnished several base maps.

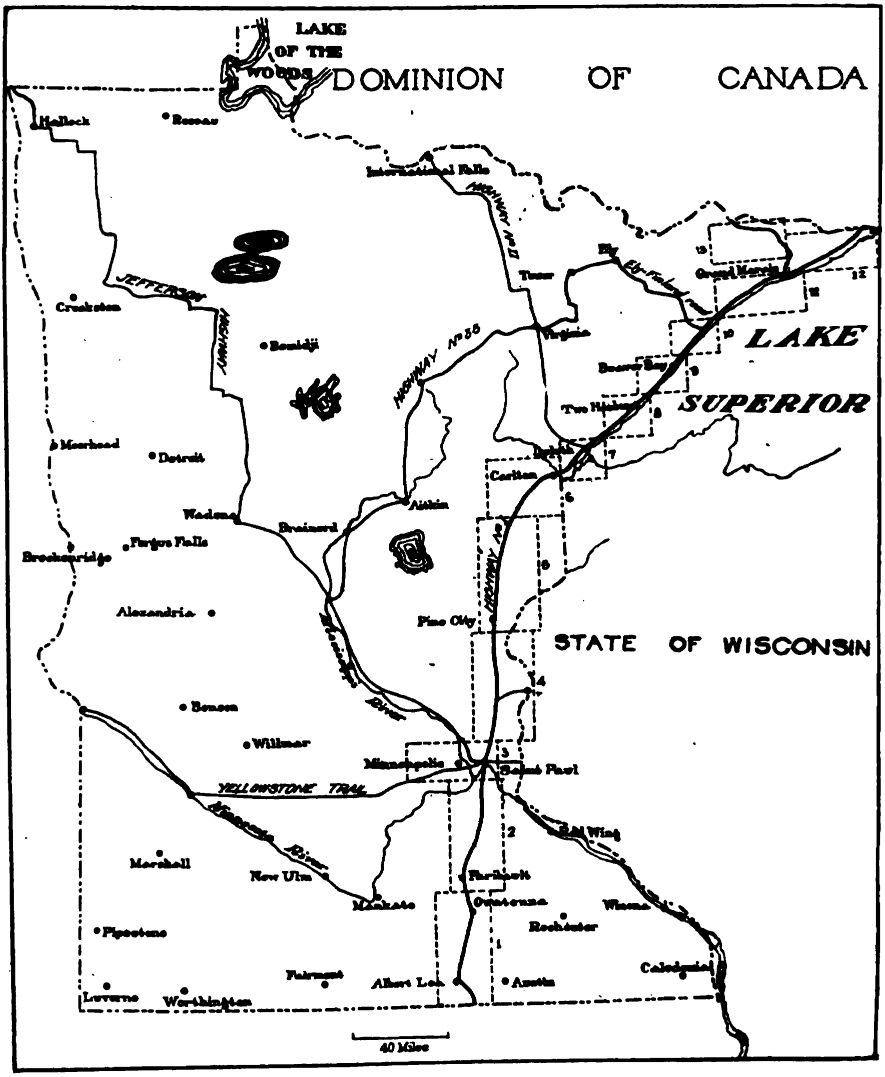

FIGURE I. KEY MAP SHOWING THE ROUTE OF HIGHWAY NO. I AND THE AREA COVERED BY EACH ROUTE MAP

The writer is especially indebted to Dr. W. H. Emmons, Dr. F. F. Grout, and Dr. C. R. Stauffer, of the Department of Geology of the University of Minnesota, for help and criticism. Dr. Grout contributed most of the field data on the Duluth region and Mr. R. D. Harvey assisted greatly in the field work.

Inasmuch as the book is popular in its nature, no attempt has been made to give detailed footnote references.

It should be emphasized that the information contained in this bulletin is but a small part of that available on the state. The Minnesota Geological Survey has a series of bulletins with more detailed information on particular regions and materials, and still others are being prepared. Those interested should send to the survey for a list of its publications.

CHAPTER II

GENERAL CONDITIONS IN, AND GEOLOGY OF, MINNESOTA

Minnesota received its name from the Minnesota River which is the largest river that lies wholly within the state. This river was called the St. Peter's by early English and French explorers. The territorial legislature succeeded in having the aboriginal name restored. Dr. Folwell has recently discussed[1] the origin and meaning of the name. The meaning most generally accepted is "clouded water," or, more poetically, "sky-tinted water," but Dr. Folwell suggests that the word may have been derived from the Dakota word "Minisota," meaning invisible or lost water, referring to the fact that the river empties into the larger Mississippi and thus loses its identity, or more probably to the fact that Pike Island hides the mouth from the view of the voyager on the Mississippi.

NOTES ON THE HISTORY OF THE STATE

The following notes give a few details of the early history of the state, which has been replete with interesting events. Dr. Folwell's four-volume work should be referred to for a comprehensive review of Minnesota history.

There is some doubt as to the identity of the first white men to visit the area now included within the state, but it is probable that two Frenchmen, Medard Chouart (Sieur de Groseillers), and Pierre d'Esprit (Sieur de Radisson), visited the region in 1654. In 1673 Louis Joliet and Father Marquette discovered the upper Mississippi, entering it at the mouth of the Wisconsin, but they did not visit Minnesota territory. Daniel Greysolon (Sieur du Luth) visited the head of Lake Superior in 1679 and then penetrated inland as far as Mille Lacs. In the following year he visited the Mississippi.

Father Hennepin was a member of the first party of white men to ascend the Mississippi to the present sites of St. Paul and Minneapolis. He discovered and named St. Anthony Falls in 1680. The area now included in Minnesota was formally claimed for France by La Salle at a ceremony at the mouth of the Mississippi, April 9, 1682.

Many other French expeditions visited the region and some established posts, but these were not permanent. Probably the first somewhat permanent settlement was the trading post established at Grand Portage Bay, Lake Superior, about 1770. In 1794 a trading post was established at Sandy Lake in the central part of Aitkin County.

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[1] Folwell, W. W., A history of Minnesota, vol. 1, pp. 455-57. St. Paul, 1922.

The first, and for some time the principal, settlement in southern Minnesota was begun when a United States Army detachment occupied a camp then called St. Peter's, near the present site of Mendota in 1819. Later the army camp was moved to the present site of Fort Snelling, and St. Peter's, later called Mendota, remained a trading post.

Minnesota was made a territory in March, 1849; the act giving authority for the organization of a state government was passed in 1857; and the state was admitted to the Union on May 11, 1858.

CLIMATE OF MINNESOTA[2]

The climate of Minnesota is much like that of the other northern states of the Middle West. It has the extremes of temperatures and moderate rainfall common to inland areas. The mean annual temperature is about 42°. The coldest months are January and February, with a mean temperature of about 10°. July is the warmest month with an average temperature of 69°. The highest temperature recorded in the state is 107° and the lowest 59° below zero. Temperatures above 100° are rare, many summers passing without that mark being approached. Temperatures below —20° are usually of short duration.

The average date of the last killing frost varies from May 1 in some southern sections to June 5 in the extreme northern portion of the state, near Lake of the Woods. The average date of first killing frost varies from September 1 in the northern portion to October 5 along the Mississippi Valley. Thus the longest growing season is 160 days and the shortest about 100 days.

Precipitation is abundant, with a variation from 32 inches in the eastern part of the state to 20 in the northwest corner. The average for the state for the years 1896 to 1914 was 27.72 inches. The rainfall is rather evenly distributed over the entire growing season. The snowfall averages from 24 to 54 inches and is heaviest in the northern portion of the state. Sunshine is abundant and this combined with the generally cool summers, especially in the northern portion of the state, makes the myriads of lakes increasingly popular as places at which to spend a summer vacation. The cool breezes from Lake Superior are always welcome to those who have suffered the heat of less favored parts of the country. Heavy coats are useful at almost any time along the north shore of the lake. The great depth of the lake is doubtless the reason for its maintaining an average low temperature, thus affecting the temperature of near by land areas.

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[2] Abstracted from U. G. Purssell, Minnesota Geological Survey Bull. No. 13, ch. ii.

TOPOGRAPHY OF MINNESOTA[3]

GENERAL STATEMENT

The position of Minnesota is near the center of the North American Continent, and the state embraces an area of 84,682 square miles, of which about 93 per cent is land and 7 per cent, water. Its extreme length is nearly 400 miles, from latitude 43° 30′, at the Iowa line, to a point about 23 miles north of the 49th parallel, in the projection known as the Northwest Angle, northwest of Lake of the Woods. The greatest width is 367 miles, but the average width is only about 225 miles, or but little more than half of the length.

Minnesota presents more variety in surface features than most of the north central states, yet a great part of its surface is level or only gently undulating. The flattest portion falls largely in the northwest quarter, and was once the bed of the glacial Lake Agassiz, a lake held in on the north, in central Canada, by the great ice sheet. The roughest portion is in the northeastern quarter within the area crossed by Highway No. 1. This part is composed largely of volcanic formations and iron-bearing rocks which, though glaciated, were not everywhere buried beneath the glacial deposits. In the southeastern part of the state deep erosion valleys along the Mississippi and its tributaries present bold rock bluffs 300 to 600 feet high. The interior and southern parts of the state have features due almost entirely to the work of the great ice sheets, which at successive times, and from different directions, overspread Minnesota. (See page 18.) The glacial desposits comprise an intricate system of moraines with undulating to hilly surface, associated with which are level outwash plains of sand and gravel, and gently undulating intermorainic till plains.

ALTITUDE

The altitude of Minnesota ranges from 602 feet, the level of Lake Superior, up to 2230 feet, on high rock hills in the northeast part of the state, in western Cook County. A large part of the state falls between 1000 and 1500 feet. The average altitude is not far from 1200 feet. The portions above 1500 feet lie chiefly in two areas, one at the northeast and one at the southwest corner of the state, though there is a good sized area around the sources of the Mississippi River in the western part, and several smaller areas in that vicinity; one of these in the southern part of Otter Tail County is known as the Leaf Hills. The altitude of the elevated area in the northeastern part includes several small areas, chiefly in Cook County, that rise above 2000 feet. The portions below 1000 feet fall in two areas widely separated except for a connecting line along the

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[3] Abstracted from Leverett and Sardeson, Minnesota Geological Survey Bull. 13, ch. i.

Minnesota Valley, one being on the western edge of the state and the other on the eastern. There is also a narrow strip bordering Lake Superior.

RELIEF

The most conspicuous relief is found in the "Sawtooth Range" and other prominent ridges that closely border Lake Superior and which rise abruptly from 500 to 900 above the lake. The rock ranges lying back from the shore, though more elevated than those fronting on the lake, seldom rise more than from 200 to 300 feet above the swamps and lakes among them. In fact several of the lakes of Cook County are above 1900 feet or within 300 feet of the level of the highest points in the state. The most prominent part of the Mesabi Iron Range in St. Louis County rises from 400 to 450 feet above bordering plains.

DRAINAGE

The drainage of Minnesota is widely divergent, part of it leading to the Gulf of Mexico, part to the Gulf of St. Lawrence, and part to Hudson Bay. The Gulf of Mexico receives about 57 per cent, the St. Lawrence less than 9 per cent, and Hudson Bay fully 34 per cent of the drainage. There was a time, however, after the glacial ice had melted from Minnesota but was still occupying the northeast part of the Superior basin and neighboring parts of Ontario and Manitoba, when all the drainage was southward to the Gulf of Mexico. The western Superior basin then overflowed into the St. Croix River, while the Red River drainage basin, largely covered by Lake Agassiz, drained southward through Lakes Traverse and Bigstone into the Minnesota Valley.

The drainage to the south, or Gulf of Mexico, has generally a gentle descent, and waterfalls are rather rare, though the Mississippi has notable falls at Minneapolis and there are one or more falls or rapids on several of the tributaries. The drainage to Lake Superior is generally rapid and nearly every stream has several cascades. There is, however, a wide area of the upper St. Louis basin in which that stream and its tributaries have relatively gentle descent for many miles. The Hudson Bay drainage has a few rapids and waterfalls in the headwater part of Rainy River and its tributaries.

LAKES

Throughout much of Minnesota, except the northwest, southwest, and southeast corners, small lakes are a common feature. They usually occupy basins among the moraine ridges and knolls and on the outwash plains, but occur to some extent also on the till plains and among rock knobs. The combined area of the lakes within the state is estimated to be about 5650 square miles, or nearly 7 per cent of the entire area. The largest lake is Red Lake, a very shallow body of water with an area of

440 squares miles. Other large lakes are Mille Lacs, also very shallow, Leech, Winnibigoshish, and Minnetonka. Minnetonka and the southern part of Leech Lake extend into a network of deep depressions among morainic ridges, but the other lakes are largely in plains that are slightly below the neighboring districts, partly morainic and partly plain.

GENERAL GEOLOGY OF THE REGION

NOTE.—Definitions of geologic terms may be found in the Glossary in the back of the book.

In order to understand and appreciate the many features which may be seen in passing along the highways, it is necessary to have as a background a general knowledge of the development of rocks and other features of the earth. The following notes may assist the reader to understand the descriptions.

In general the southern part of Highway No. 1 passes through a region mostly covered with glacial débris, but with outcrops of rock along the Mississippi River and some of the lesser streams. In the vicinity of Duluth and along the north shore of Lake Superior outcrops of solid rock are abundant and very old slates and lava flows are the important types.

The rocks of the earth are grouped according to their age and each subdivision of geologic time, as determined by a study of the succession of rocks and of their enclosed fossils, has been given an appropriate name. A consideration of the basis for this subdivision cannot be taken up here, but any textbook of general geology may be referred to for the details. This arrangement of the rocks into subdivisions has been the result of long studies by many investigators.

Not all of the various geologic periods are represented by the rocks in a given area, and only the periods represented in the areas adjacent to Highway No. 1 are discussed here. The table on pages 10 and 11 lists the rocks which are exposed in Minnesota with a star marking those which exist along Highway No. 1. A table of geologic time is given to show by comparison the parts represented in Minnesota. Figure 2 is a generalized geologic map of the state showing the distribution of the various formations either as outcrops or beneath a cover of soil and glacial drift.

The oldest rocks, known as the Archean (Ancient) rocks, are exposed in northern Minnesota but not in the region traversed by Highway No. 1. Above the Archean are rocks which belong to the Algonkian period which is subdivided into the Huronian and Keweenawan. The Huronian is composed of several formations, but only the upper ones are exposed along Highway No. 1. Perhaps the thickest part of the Huronian is the slate formation which overlies the iron formations of the region and forms the upper part of the Huronian sedimentary series. On the Mesabi Range this is known as the Virginia slate. Some of the other slates found in northern Minnesota, in Carlton and Cook counties, are usually considerc to be equivalent in age to the Virginia slate. These are known as tl Carlton and Rove slates.

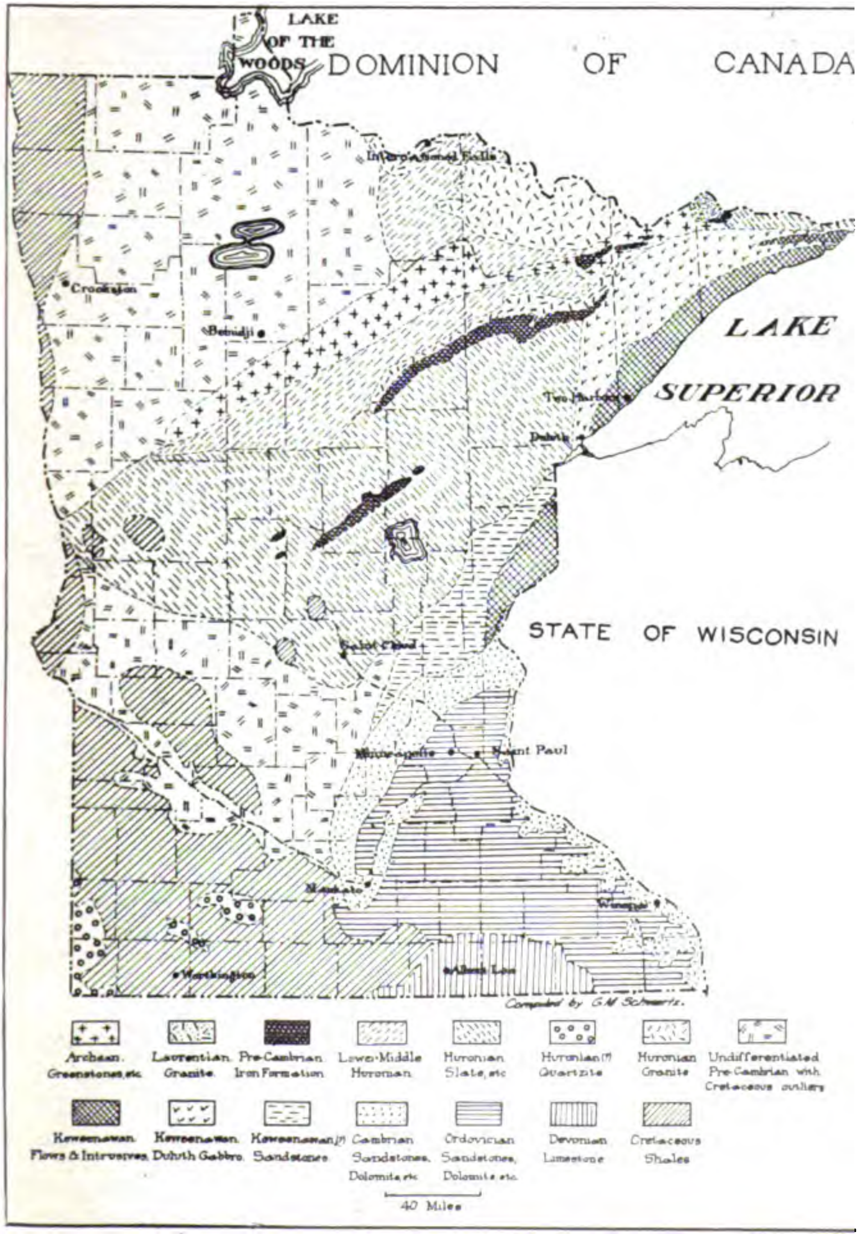


FIGURE 2. GENERALIZED GEOLOGIC MAP OF MINNESOTA. COMPILED FROM THE PUBLICA
TIONS AND FIELD NOTES OF THE MINNESOTA GEOLOGICAL SURVEY AND THE PUBLICA
TIONS OF THE UNITED STATES GEOLOGICAL SURVEY

GROUP	SYSTEM OR SERIES			FORMATION	APPROXIMATE MAXIMUM THICKNESS (FEET)	CHARACTER OF STRATA
CENO-ZOIC	QUATERNARY	RECENT*				Lake or river silt
		GLACIAL* PERIOD			600±	Glacial drift, loess, etc.
MESO-ZOIC	CRETACEOUS			Benton shale*	500	Clays and shales
				Dakota sandstone		Sandstone.
PALEOZOIC	DEVONIAN			Cedar Valley limestone	100	Limestones.
	ORDOVICIAN			Maquoketa shale.	100	Shales and limestones
				Galena limestone*	100	Limestone with some shale
				Decorah shale.*	65	Shale and some limestone
				Platteville limestone.*	30	Dolomitic limestone
				St. Peter sandstone.*	200	Sandstone with a little shale.
				Shakopee dolomite.*	100	Sandy dolomite.
				Oneota dolomite.	200	Buff to reddish dolomite.
	CAMBRIAN			Jordan sandstone.	200	White to brown sandstone.
				St Lawrence formation	200	Buff dolomite with green shale and sandstone
				Franconia sandstone.*	100	White sandstone and green sand.
				Dresbach sandstone and underlying sandstone+shale.*	450	White sandstone with interbedded shales and limestone.
PROTEROZOIC	ALGONKIAN?			Red clastic series.*	2250	Red sandstones and shales.
	ALGONKIAN	KEWEENAWAN		Conglomerates and sandstones.*	500	Conglomerate and sandstones
				Eruptives.*	?	Granites, diabases, gabbros, basalts, etc
		HURONIAN	UPPER HURONIAN (ANIMIKIE)	Acid and basic intrusives	?	
				Virginia, Rove, and Carlton slates.*	3000±	Slates
				Biwabik and Gunflint iron formations	800	Taconite, iron ore, ferruginous chert, etc.
				Pokegama quartzite	200	Quartzite, slate and conglomerate
			LOWER-MIDDLE HURONIAN	Giants Range granite and other intrusives	?	Gray to pink granite, granite porphyry, etc
				Slate, graywacke, and conglomerate	5000	Green to gray slates graywackes and conglomerates
ARCHE-OZOIC	ARCHEAN	LAURENTIAN		Granites, gneisses, and porphyries	?	Granites, porphyries, etc.
		KEEWATIN		Soudan formation	?	Chert and jasper. Iron ore
				Schists, porphyries, and greenstone	?	Green schists, greenstone, porphyries, etc.

GEOLOGIC COLUMN OF MINNESOTA

Note- Formations marked * are found in the regions traversed by Highway No. 1

ERA		PERIOD	CHARACTERISTIC LIFE	DURATION ACCORDING TO VARIOUS ESTIMATES Millions of years
CENOZOIC Recent life	QUATERNARY	RECENT	'Age of man' Animals and plants of modern type.	1 to 5
		GLACIAL PERIOD		
	TERTIARY	PLIOCENE MIOCENE OLIGOCENE EOCENE	'Age of mammals' Possibly first appearance of man. Rise and development of highest order of plants.	
MESOZOIC Intermediate life		CRETACEOUS	'Age of reptiles' Rise and culmination of huge land reptiles (dinosaurs), of shell-fish with complexly partitioned coiled shells (ammonites), and of great flying reptiles. First appearance (in Jurassic) of birds and mammals; of cycads, an order of palmlike plants (in Triassic); and of angiospermous plants among which are palms and hardwoods (in Cretaceous).	4 to 10
		JURASSIC		
		TRIASSIC		
PALEOZOIC Old life.		PERMIAN	'Age of amphibians' Dominance of club-mosses (lycopods) and plants of horsetail and fern types. Primitive flowering plants and earliest cone-bearing trees. Begining of backboned land animals (land vertebrates). Insects. Animals with nautilus-like coiled shells (ammonites) and sharks abundant	17 to 25
		PENNSYLVANIAN		
		MISSISSIPPIAN		
		DEVONIAN	'Age of fishes' Shellfish (mollusks) also abundant. Rise of amphibians and land plants.	
		SILURIAN	Shell-forming sea animals dominant, especially those related to the nautilus (cephalopods). Rise and culmination of the marine animals sometimes known as sea lilies (crinoids) and of giant scorpion like crustaceans (eurypterids) Rise of fishes and reef-building corals.	
		ORDOVICIAN	Shell-forming sea animals, especially cephalopods and brachiopods abundant. Culmination of the marine crustaceans known as the trilobites. First trace of insect life and of fishes.	
		CAMBRIAN	Trilobites and brachiopods most characteristic animals Seaweeds (algae) abundant. No trace of land animals found.	
PROTEROZOIC Primordial life		ALGONKIAN	First life that has left distinct record. Crustaceans, brachiopods, dacteria, and seaweeds.	
ARCHEOZOIC		ARCHEAN	No fossils found except possible algae.	50+

PRINCIPAL DIVISIONS OF GEOLOGIC TIME

HURONIAN SLATES, EROSION, SEDIMENTATION, AND METAMORPHISM

Huronian slates comprise the oldest rocks actually exposed along Highway No. 1. They may be seen at several places along the highway in Carlton County, notably at the bridge over the St. Louis River and along the river through Jay Cooke Park. The Rove slate, which is about equivalent in age, is exposed in the extreme northeastern part of Minnesota, from Grand Portage north to the boundary at the Pigeon River and extending westward to Gunflint Lake. The formations, as the names indicate, are dominantly slate, but the Rove formation particularly has a considerable variation and much graywacke as well as minor amounts of quartzite and conglomerate are found within it.

The material from which the slates and associated rocks formed was laid down by processes of sedimentation and was subsequently subjected to metamorphism. The origin of these rocks may then be briefly explained as follows. Wherever land areas are exposed they are subject to the continual action of water, wind, or ice, and in addition to the chemical action of solutions, that is, of water with various dissolved materials. In this manner rocks are broken down and become subject to transportation by the same agencies, but water is normally the important transporting and depositing agency. The material is carried in solution and in suspension, as may be determined by analyzing any river water. When a river flows into the ocean or a lake its velocity is checked and the material carried in suspension is dropped. If this takes place near the mouth a delta is formed, if ocean currents and waves are active the material may be carried long distances and spread out in extensive but thinner beds. The material carried in suspension forms mud, sand, or gravel depending on the size of the particles. The variability of the constituents may be observed in any outcrops of sedimentary rocks or in material deposited by present day streams. Materials carried in solution, as calcium carbonate, may be precipitated by chemical or organic processes, forming limestone or dolomite.

Where the sediments noted above continue to pile up, those beneath are subject to considerable compression, and they are more or less compacted and usually cemented. If the sediments have been deposited in relatively shallow arms of the ocean, earth movements may result in the elevation of the bed above the sea level and when the upper beds are removed by erosion those beneath are found to have consolidated and form the ordinary sedimentary rocks. The sands have formed sandstone, the mud has changed to shale, the calcareous deposits to limestone and dolomite; gravel, where present, has formed conglomerate. These five types of rock comprise by far the greater part of all sedimentary rocks. Examples of these rocks may be seen along the Mississippi River in

Minneapolis and St. Paul, at Faribault, Northfield, Taylors Falls, Sandstone, and other places noted in the following chapters. As a result of their deposition in water, they are characteristically layered or bedded and may have ripple marks, fossils, and other structures. The types of fossils indicate whether the beds were formed in fresh or salt waters as the animals which live in the ocean are distinctly different from those found in fresh water lakes and rivers.

When sedimentary rocks are very deeply buried and subject to the action of pressure, heat, and movement, they undergo much more profound changes than is the case when unconsolidated sediments are transformed to sedimentary rocks. This change is called metamorphism (change of form) and rocks which have undergone a transformation in this way are called metamorphic rocks. It is known from their composition and original texture, as well as by gradations which have been found in various parts of the world, that shales are thus transformed to slates, and sandstones to quartzites. These transformations naturally involve changes in chemical and mineral composition, as well as in texture and structure. The rocks become hard, cleavage or parting characteristic of slate is developed, and the rocks may be folded and faulted as are the slates along the St. Louis River, but even in that case the original bedding may be distinguished by light and dark bands and by a parting along the bedding. (See Plate 11-c.)

KEWEENAWAN ROCKS, LAVAS, AND IGNEOUS PROCESSES

Directly overlying the slates in the Duluth-Carlton area is a great series of rocks, largely igneous, which are known as Keweenawan rocks from the extensive exposures on Keweenaw Point, Michigan. Similar rocks are exposed at Taylors Falls, on the Snake River east of Pine City, and along the north shore of Lake Superior from Duluth to Grand Portage Bay. (See Figure 2.)

The Keweenawan rocks consist mainly of basalt and rhyolite lava flows, and coarse diabases, gabbro, and syenite, with lesser amounts of sandstone, shale, and conglomerate.

The lava flows consist of rock which was poured out on the surface in a molten condition and thence flowed out into broad sheets. The question immediately arises, how do we know that these rocks were formed as lava flows? If a large outcrop of these rocks is examined, such, for example, as is found along shore below the Two Harbors Tourist Park, where a series of four flows are exposed, it may be seen that there is a dense, massive layer of dark rock which grades upward into a band which is spotted with light colored mineral filling rounded holes. It is known from comparison with present day lava flows, such as occur in the Hawaiian Islands, that this vesicular or amygdaloidal layer is formed by gas bubbles rising to the top of the flow. Subsequently minerals are deposited in the holes. In some cases the upper surface of a flow is much broken or brecciated and at places sand and pebbles are incorporated in the top of the flow. The sand and pebbles may form separate beds of conglomerate as on the Snake River east of Pine City, or sandstone as at Good Harbor Bay near Grand Marias. The lava flows which border Lake Superior are so extensive that it is doubtful if they could have issued from volcanoes such as those which form conical mountains, but it is believed that they issued from large fissures and spread out over the surrounding country like those in Iceland in historic time. The rocks formed from lava flows are characteristically dense and fine grained as a result of their cooling so quickly that large crystals did not have time to grow.

After the lava flows had been poured out, the molten material (magma) continued to work its way upward, but at places it could not reach the surface and it forced its way between the flows and other rocks and formed huge masses of intrusive rocks now recognized as gabbro, diabase, and syenite. The Duluth gabbro is the largest mass of this material. It extends from Duluth north and east in a broad belt reaching Lake Superior at the Reservation River, twenty-five miles east of Grand Marais. At many places along its border it has affected by its great heat the rocks with which it came in contact. This is true, for example, at Short Line Park near Duluth. (See page 66.) This mass was so large that the molten material segregated more or less after intrusion and near the top the black gabbro grades to "red rock" (syenite or granite). Diabase and gabbro rocks also are found as sills and dikes in the lava flows at places from Duluth to Grand Portage Bay and in the slates north of that point. At places, for example on shore near Encampment Island, the diabase has clearly tipped up the flows by the force of its intrusion.

The gabbros, diabases, and syenites (red rock) are coarse grained rocks, that is the minerals which compose them may be easily recognized with the naked eye. Gabbros and diabases are characteristically dark to black rocks whereas syenites are normally red. The coarse texture is a result of the slow cooling of the mass of molten material under cover. It is known from the poor conductivity of rocks that it must have taken centuries for a mass the size of the Duluth gabbro to cool. There was probably little difference in the composition of the molten material which formed the basalt flows and the gabbro, but the difference in the time of cooling has resulted in a distinctly different texture in the two types. The intrusive rocks are hard and massive, and resist weathering better than the surrounding flows. The almost mountainous character of the north shore country is directly attributable to the presence of the numerous diabasic intrusions.

There are associated with these diabases some peculiar rocks known as anorthosites. These are composed almost entirely of feldspar and are very resistant, forming prominent white hills even in the diabase areas. They are igneous rocks, that is, they were once in a molten condition and they were brought to their present positions about the time the diabases were formed.

CAMBRIAN AND ORDOVICIAN SEDIMENTARY ROCKS

The rocks of the Huronian and Keweenawan periods are very old. They include igneous and metamorphosed sedimentary rocks. At the beginning of the Cambrian, however, volcanic activity and folding, characterized by intense pressure, ceased in this area, and even to the present time only moderate changes have affected the rocks. The Cambrian and later rocks are easily recognizable and in some of them abundant remains of life (fossils) are found. (See table on page 11, and Plate I.)

Cambrian rocks are abundantly exposed along the St. Croix and Mississippi rivers from Chisago County to the southern boundary of the state. (See Figure 2.) The only place where they may be seen in the region described in this bulletin is at Taylors Falls. The rocks which make up the Cambrian include all of the common sedimentary rocks: sandstone, dolomite, limestone, shale, and conglomerate. Sandstone is probably the most abundant and certainly the most conspicuous.

The origin of these rocks has been discussed above under sedimentation, and they afford many examples of the processes noted. The evidence for the conclusion that the Cambrian rocks are younger than the Keweenawan lava flows may be seen at Taylors Falls, where a conglomerate overlies the flows and is composed chiefly of rounded boulders and pebbles of the basalt flows with a matrix of sand which contains characteristic Cambrian fossils. The conglomerate grades upward into sandstone which forms bluffs below the "Dalles." (See page 50.) The boulders doubtless represent blocks broken from the cliffs of Keweenawan rocks by wave action and later the Cambrian sea became deeper and covered them with sand.

Immediately overlying the Cambrian rocks is a somewhat similar series belonging to the Ordovician period. The chief reason for setting this series apart from the Cambrian is the marked difference in the type of life represented by fossil remains. (See table on page 11.) These remains indicate a progressive development of animal life to higher forms. Referring to the table on page 10, it may be seen that seven formations comprise the Ordovician strata in Minnesota. Of these all but the lowest and highest are exposed in the area covered by this report. These rocks are exclusively sedimentary and consist of sandstones, dolomites, limestones, and shales.

Plate I

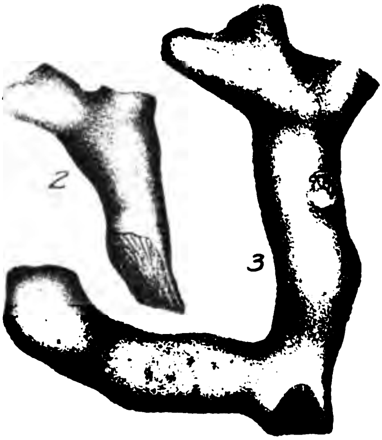
Common Types of Fossils Found in Ordovician Rocks in Minnesota

(Any or all of these, and many others, may be found in the Twin Cities)

1. A horn coral (*Streptelasma profundum*). Minneapolis.
2-3. Bryozoans, small and average size (*Batostoma minnesotense*). Minneapolis.
4. A brachiopod (*Strophomena incurvata*). Minneapolis and St. Paul.
5. A brachiopod (*Pianodema subaequata*). Minneapolis.
6. A brachiopod (*Orthis tricenaria*). Minneapolis.
7. A brachiopod (*Rhyncotrema minnesotense*). Minneapolis.
8. A pelecypod (*Vanuxemia obtusifrons*). Minneapolis.
9. A gastropod (*Trochonema beloitense*). Minneapolis and St. Paul.
10. A gastropod (*Clathrospira subconica*). Minneapolis.
11. A gastropod (*Trochonema umbilicatum*). Minneapolis and St. Paul.
12. A cephalopod (*Onoceras carveri*). Minneapolis.
13-14. A trilobite (*Pterygometopus intermedius*). St. Paul.

PLATE I

1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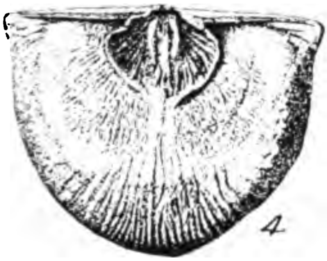
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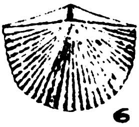
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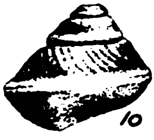
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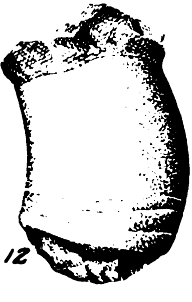
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The Ordovician rocks are confined to the southern part of the state and are not exposed along Highway No. 1 north of Minneapolis and St. Paul. The southernmost exposure along the highway is just north of Owatonna. The St. Peter sandstone and Platteville limestone are well exposed at Faribault and along the Mississippi River through Minneapolis and St. Paul.

The Ordovician rocks were for the most part deposited in ocean waters and most of the formations, especially the Decorah shale and Platteville limestone, have abundant fossil remains of animals which lived in the early seas. The St. Peter sandstone is a remarkably pure white sandstone which is so little cemented that it may be crumbled with the hand. It is composed almost entirely of white rounded quartz grains. A detailed study of the grains indicates that they have been worn by being blown about by the wind, but its layered condition and the occurrence of fossils in it at St. Paul show that it was finally deposited in the sea. On account of its purity it has been used for glass-making, and the Ford Motor Company has recently examined the Minnesota occurrences with that possibility in mind. The formation is very widespread as it extends as far east as Detroit, Michigan, and southward to Arkansas.

Geologic periods not represented in Minnesota.—There are no beds exposed along Highway No. 1 of the ages between the Ordovician and the Glacial period. From studies elsewhere it is known that a great series of beds represent this interval, but if they were ever present in this region, they have been washed away. It is known from drilling records that relatively thin beds of Devonian and Cretaceous rocks are present in Freeborn and Steele counties. Some of the great series of rocks not represented in Minnesota include, for example, the series that contain the great coal beds of the various fields from Iowa, Missouri, and Arkansas to Pennsylvania.

THE GREAT ICE AGE—GLACIATION

The last great event which preceded the establishment of present conditions in Minnesota was the advance of great ice sheets which covered large parts of North America. It has been established by means of the scratches on the rocks that the ice worked outward from three great centers: an eastern center in Labrador (Labradorean); an interior point just west of Hudson Bay (Keewatin), and the third in the Rocky Mountains (Cordillerean). Practically the entire area of Minnesota was covered by the ice at some time. Ice from both the Labradorean and Keewatin centers invaded Minnesota. The ice would advance from one direction and after a time melt back and later a lobe would advance from another direction. These movements have also been proved by the nature of the drift. Outcrops showing scratches are referred to in the detailed descriptions in succeeding chapters. At least three drift sheets laid down by different advances of the glacier are exposed along Highway No. 1. These three sheets are known as the old gray drift, the red drift, and the young gray drift. The old gray drift was deposited by one of the earlier advances of the ice, usually called the Kansan. The red and young gray sheets are usually referred to the Wisconsin stage of glaciation. The red drift was deposited by a lobe which came from the northeast, whereas the young gray material came from the northwest. Different types of rocks in the regions from which the ice came account for the differences in the types of material.

As a result of the invasion of the ice the nature of the surface in Minnesota was greatly changed. Valleys and other depressions were filled, rock hills were scoured off, heaps of glacial débris were piled up, forming ridges and hills.

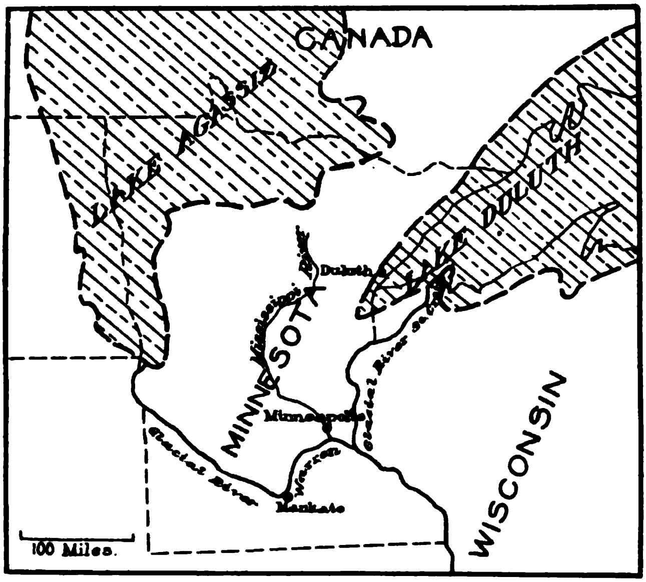

FIGURE 3. SKETCH MAP SHOWING PORTIONS OF GLACIAL LAKES AGASSIZ AND DULUTH. LAKE AGASSIZ DRAINED SOUTHWARD ALONG THE PRESENT VALLEY OF THE MINNESOTA RIVER. LAKE DULUTH DRAINED INTO THE ST. CROIX RIVER. BASED ON MAPS BY UPHAM

There are three main types of deposits left by the glaciers and the waters which poured out from their margins. The thick hilly accumulation made at the edges of the ice sheet when the margin remained stationary for some time is known as a *terminal moraine*. When the glacier melts from a large area it leaves a heterogeneous mass of débris which covers the surface to a varying depth forming the *ground moraine.* Numerous streams flow out from the ice sheet and spread a broad sheet of silt, sand, and gravel in front of the terminal moraine, forming what is known as an *outwash plain.* The same material found along stream channels is called simply an outwash deposit or a valley train. There are numerous examples of each of these types which have been described in the following chapters.

Where streams formed tunnels under the ice, the tunnel often became more or less filled with the coarser material carried by the stream. When the ice melted this material formed ridges known as eskers. (See page 30.) Where the waters emerged from the ice, hills of gravel were often formed and these are known as kames.

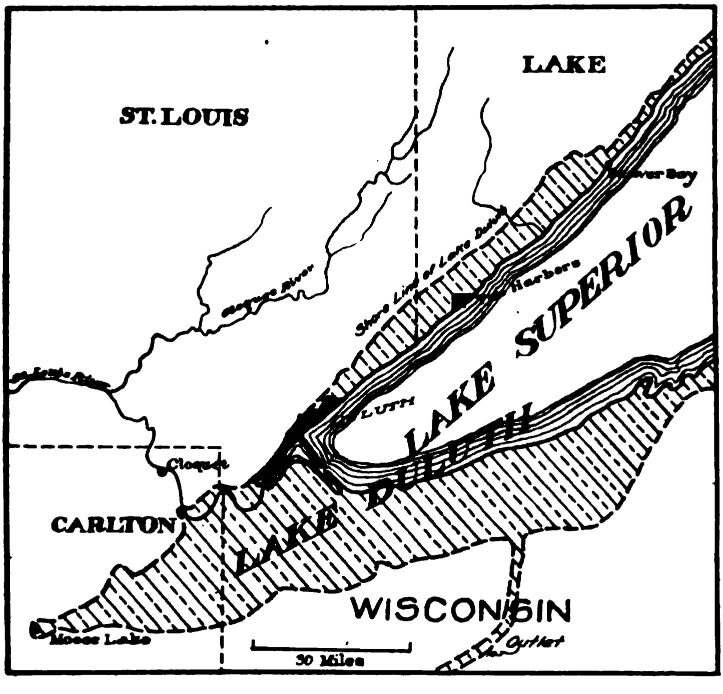

FIGURE 4. SKETCH MAP SHOWING THE RELATION OF LAKE DULUTH TO LAKE SUPERIOR. AFTER MARTIN AND OTHERS. UNITED STATES GEOLOGICAL SURVEY MONOGRAPH 52

The work of the glaciers was not confined to direct deposits, but the large amount of water furnished by the melting produced important effects. Where the natural drainage of the region was in the direction occupied by the glacier, extensive lakes were formed in front of the ice. This was the case in the region now occupied by Lake Superior. When much of the present lake was occupied by ice and the St. Lawrence outlet was thus cut off, the lake drained to the southward into the St. Croix River, thence into the Mississippi (see Figure 3), and Lake Superior was several hundred feet higher than at present and covered a much larger area. (See Figure 4.) Likewise the drainage from northwestern Minnesota, which would otherwise have flowed northward as it does now, was blocked and a large lake known as Lake Agassiz was formed, which extended through northwestern Minnesota, eastern North Dakota, and northward over a very large area in Canada. This lake at first drained southward into the Minnesota River (see Figure 3), and the large amounts of water thus supplied rapidly eroded a great valley and gorge as may be seen at Fort Snelling and above. Later, when the glaciers had ceased to exist, the amount of water in this and many other streams decreased greatly and now the diminished streams often seem out of proportion to their relatively large valleys. As a result of this diminished water supply the dwindling streams were unable to carry away the large quantities of rock débris supplied to them and it accumulated in the gorges, such as that of the Mississippi which through St. Paul is known to be thus filled to a depth of fully 100 feet.

After the ice had retreated to the north and the glacial lakes had decreased or disappeared, as water from the melting ice diminished, conditions became much as they are now. Vegetation began to flourish on the barren wastes, forests sprang up, lakes occupied the undrained depressions formed by the irregular deposition of débris by the ice, and the streams found new courses or occupied the partially filled old channels. Thus gradually the present aspect of the country was developed except for the changes made by man in the last century.

CHAPTER III

HIGHWAY NO. 1 FROM THE SOUTH STATE LINE TO THE TWIN CITIES

Freeborn County

(Total area 701.94 square miles; covered by water 20.73 square miles)

Note.—In following descriptions of the route frequent reference should be made to the maps which accompany various parts. It is assumed that Chapter II has been read. Definitions of geologic terms are given in the Glossary.

The traveler following the Jefferson Highway northward through Iowa enters Minnesota on State Trunk Highway Number 1 near the southeast corner of Freeborn County. This county, in common with practically all of the counties of southern Minnesota, is noted for its very fertile soil which produces large crops of corn, oats, wheat, hay, and other products. Dairying is an important industry. The county is composed of twenty government townships extending five east and west and four north and south. It was established February 20, 1885, and was named in honor of William Freeborn, a member of the council of the territorial legislature.

Where Highway No. 1 begins at the state line (see Route Map No. 1) the topography or surface of the land is gently undulating and the soil consists of material brought down by the glaciers (see page 18) which was deposited in various ways and forms. To the east of the road is an oak grove which represents the type of timber originally found on the rougher portions of the land and along the streams. To the west is a level stretch of prairie which was not originally timbered.

Gordonsville
Population[1] 136
Elevation 1213 feet

Gordonsville is a village on the Chicago, Rock Island and Pacific (Rock Island) Railway, a mile north of the state line. North of the village the undulating surface may be seen only to the east of the road and the traveler passes through almost level prairie broken only by groves of trees which have been planted around the farm buildings. The road turns west toward Glenville and wooded areas are numerous along the sluggish Shell Rock River which flows southward from Lake Albert Lea.

Glenville
Population 379
Elevation 1235 feet

After passing through Glenville the road turns north along the west side of Shell Rock River. To the west lies an almost unbroken prairie while the banks of the stream are wooded. Gravel and sand deposits are abundant near the river and have been opened for local use at several places. The sand and gravel represent outwash material formed by large streams which poured forth from melting ice when the glacier retreated. (See page 20.)

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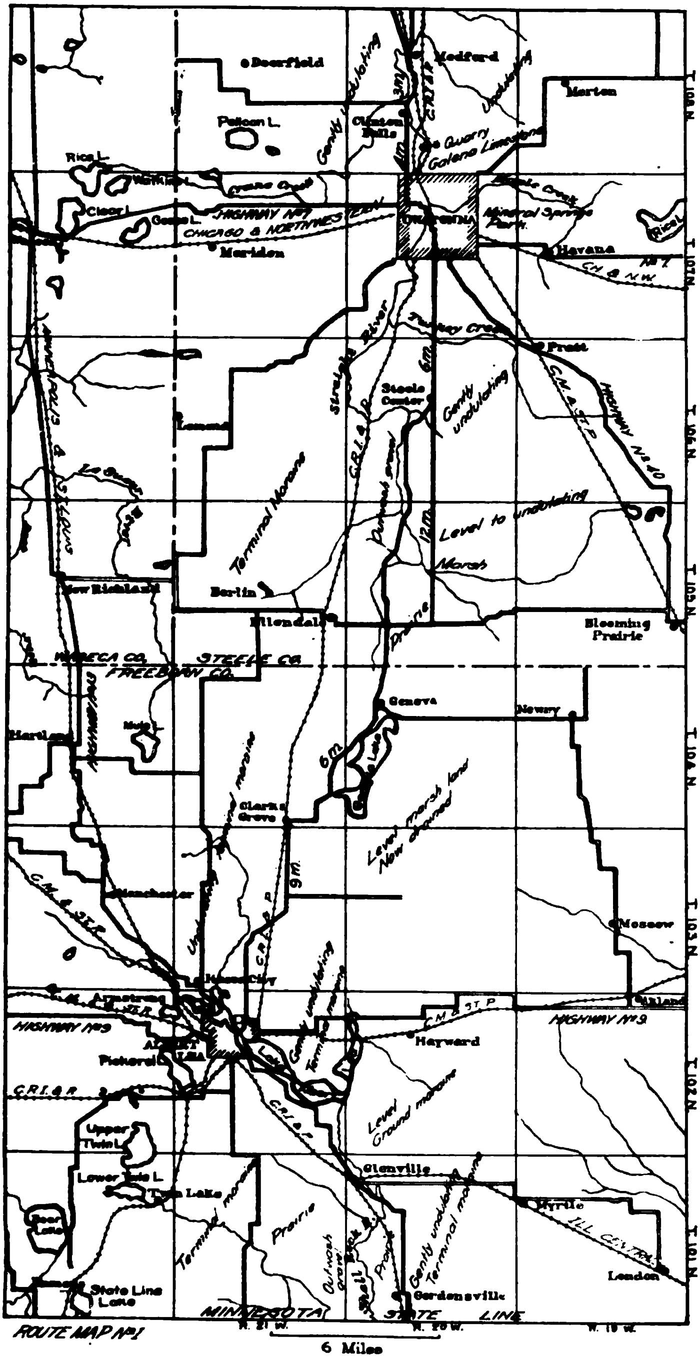
[1] Unless otherwise noted, the population is that of the last census.



HIGHWAY NO. I THROUGH FREEBORN AND STEELE COUNTIES. THE HIGHWAY IS INDICATED BY A HEAVY BLACK LINE. DISTANCES BETWEEN TOWNS ON THE ROUTE ARE GIVEN THUS, 9 M.

Lake Albert Lea.—About three miles beyond Glenville and extending to the city of Albert Lea is Lake Albert Lea. The lake, and later the city, were named in honor of a United States Army officer, Albert Miller Lea, who accompanied an expedition to the region in 1835 and mapped the lakes and streams. Much of the lake is shallow and it has been a favorite resting place for migratory water fowl and for this reason the lake and a surrounding area has been designated as a state game refuge.

A gravel pit near the south end of the lake exposes stratified sand and gravel with a great variety of pebbles. The pebbles have been brought from great distances by the ice sheet or glacier and were deposited here by waters which flowed out from the front of the glacier when it remained more or less stationary for a time. Such gravel hills are sometimes known as kames. (See page 20.) The surface of the region is undulating to hilly due to the irregular material left by the ice, forming what is technically known as a terminal moraine.[2] (See page 20.) This moraine is not as characteristic as some found farther north in Minnesota but to the practiced eye it presents the same features on a smaller scale. The road follows the lake shore to the city and the attractiveness of the country is greatly increased by the trees along the shore, which are mostly oak interspersed with aspen, elm, ash, and maple.

Albert Lea
Population 8256
Elevation 1225 feet

Albert Lea is a thriving city beautifully situated on a strip of land between Fountain Lake and Lake Albert Lea. It is served by the Illinois Central; Rock Island; Chicago, Milwaukee and St. Paul; and Minneapolis and St. Louis railways. State highways Nos. 1, 9, and 13 radiate from the city. Albert Lea was first settled in 1855 and was incorporated in 1878. There are 51 manufacturing and wholesale industries in the city, of which the Wilson and Company packing plant is the largest. Fountain Lake on the north is partly surrounded by the city, and a boulevard has been constructed around it. A tourist park is located on the lake shore and is provided with many conveniences. The rolling nature of the surface especially to the west of the city is notable and is formed by the terminal moraine which trends north and south through that area. The city is mainly located on an area of outwash which lies between the moraines to the east and west of town. The moraines have formed the lakes by filling up the old drainage channels. (See page 21.)

For ten miles north of Albert Lea a rolling or undulating topography represents the northward extension of the moraines found at the city. Oak groves occupy many of the knobs and rougher portions, but most of the land is under cultivation.

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[2] For definitions and explanations of geologic terms see Glossary at end of book.

Clark's Grove, a railroad station nine miles north of Albert Lea, is named from a grove a mile east of the village in which J. Mead Clark settled in the early days. After passing Clark's Grove, Geneva Lake may be seen occupying the lowland to the east. To the west of the road the surface is undulating like that found farther south. Geneva Lake is about four miles long and one to one and one-half miles wide, but is comparatively shallow. At the end of the Glacial period it was undoubtedly much larger and extended over the marsh land to the south, and was probably connected with what was formerly Rice Lake. This lake and the surrounding marsh land has been drained leaving fertile soil which has been rapidly put under cultivation by a group of settlers from Holland. Truck farming particularly is successful.

Clark's Grove
Population 97
Elevation 1400 feet

To the north of Geneva the country is nearly level. It undoubtedly was prairie when the settlers entered it. The county line between Freeborn and Steele counties is one and one-half miles north of Geneva.

Geneva
Population 207
Elevation 1383 feet

It should be noted that no exposures of solid rock are seen in passing through Freeborn County and none has ever been found, as the glacial drift covers the rock to a considerable depth. From data in surrounding regions it is believed that Devonian (see table of formations and descriptions in Chapter II), and Ordovician rocks underlie much of the county, but Cretaceous rocks probably cover part of the older rocks beneath the drift. The glacial drift consists of three types of deposits: terminal moraines, which form the rougher portions; ground moraines, which are more widespread and form level plains or gently undulating areas; and outwash sand and gravel deposits, which are found along the streams and in the vicinity of Lake Albert Lea.

STEELE COUNTY

(Total area 430.59 square miles; covered by water 4.6 square miles)

Steele County was established in 1855 and received its name in honor of Franklin Steele, a prominent pioneer of Minneapolis.

The level prairie of Freeborn County extends to the marshy land three miles north of Steele County line. North of the marsh the country is gently rolling and a few of the knolls have oak groves. This gently undulating country extends to Owatonna, the county seat.

The Straight River.—The valley of the Straight River is just to the west of Highway No. 1, south of Owatonna. Several creeks unite in the southern part of the county to form the river which flows northward through Owatonna. The river is said to have received its name by translation of the Sioux word for straight, which is Owatonna. It is supposed that the name was given in derision as the river is very crooked. The stream is very sluggish and the valley is much larger than the present stream requires. (See page 21 for explanation.) The trees along the valley are worthy of particular note; instead of the scrub oaks which predominate farther south, one sees large elms, basswood, and oaks.

Owatonna
Population 7252
Elevation 1145 feet

Owatonna is a thriving city and a commercial center for the surrounding country. It is served by the Rock Island; Chicago, Milwaukee and St. Paul; and Chicago and Northwestern railways. Pillsbury Academy, a boys' school, occupies several large buildings on the east side of the city. A fine high school is located just north of the academy, and the State School for Indigent Children is on the west edge of town. An attractive tourist park is provided at Mineral Springs Park on Maple Creek about one mile northeast of the business center of town.

Mineral Springs Park.—Mineral springs are found in the valley at the base of a clay bluff. They probably are due to a clay seam overlying a sand or gravel bed. The water from the surrounding country flows in the gravel below the clay, and parallel to the surface, until it escapes at the low points along the creek. A deposit of iron may be noted in the ponds around the springs and the water has a slight mineral taste, but is excellent for drinking purposes. Several huge boulders of granite occur along the creek at the springs, having been left there by the glacier although they perhaps owe their exposure to erosion of the surrounding material by the creek. The boulders were probably brought down from the northern part of the state where granite is known to outcrop.

Leaving Owatonna the highway turns west and crosses the river, thence angling northwest to reach the more level country to the west of the valley. The main slopes of the valley extend about one-half mile on each side of the stream and are about fifty feet below the level of the surrounding country. Aside from the valley the surface is gently undulating and shows no unusual features.

Galena limestone.—About two miles north of Owatonna an east-west road crosses the river and at the bridge are the southernmost outcrops of solid rock seen near the route. (See Chapter II.) The rock has been quarried on both sides of the road thus giving excellent exposures. The rock is a thin-bedded, slabby limestone of Ordovician age and is a part of the Galena formation (see page 10), as is known from the fossils found in certain layers. (See Plate I.) The fossils are the remains of various types of shell-bearing animals which live only in salt water, thus showing that a very long time ago the ocean covered this area.

Continuing northward on the west side of the river one is afforded another opportunity for contrasting the topography and wooded slopes of the valley with the gently undulating surface of the prairie to the west.

Clinton Falls
Population 82

At Clinton Falls a dam furnishes water power for a small mill. Just beyond the village is a fine exposure of stratified sand and gravel where the road has been cut through the hill. Beyond this the road crosses to the east side of the river and then crosses back to the west side at Medford.

A large gravel plant to the east of the road north of Medford obtains gravel from the glacial outwash deposits along the river. The north line of Steele County is about two miles north of Medford.

Medford
Population 346
Elevation 1101 feet

One exposure of solid rock has been noted in the county and this is the only one known. A deep well at Owatonna passed through 35 feet of glacial drift, 59 feet of sandstone and clay, probably of Cretaceous age (see table of formations, page 10), then the various formations of the Ordovician, beginning with the Galena limestone and ending in the St. Peter sandstone. Most of the county is undoubtedly underlain by Cretaceous and Ordovician rocks. Like Freeborn County, this county is almost completely covered by glacial deposits consisting of irregular north-south belts of terminal and ground moraine with outwash deposits along the valley of the Straight River.

RICE COUNTY

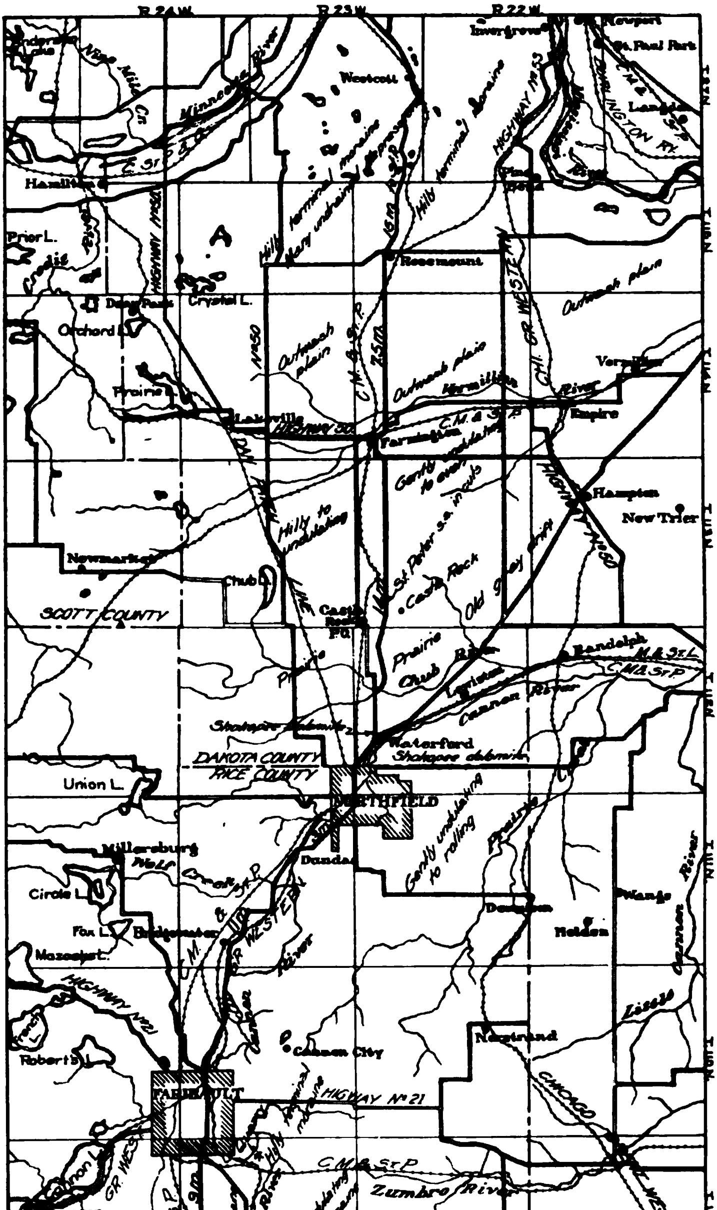
(Total area 504 square miles; covered by water 17.2 square miles)

Rice County was first settled in 1853 and was named in honor of Henry Mower Rice, one of the first United States senators from Minnesota. This county shows more relief than the two counties to the south.

Highway No. 1 has been changed recently to the west side of the Chicago, Milwaukee and St. Paul Railway for about two miles, thence following a course due north to Faribault. The road gradually leaves the valley of the Straight River and follows the rolling land to the west. From the hill tops a good view of Faribault and the high country to the east may be had.

The city of Faribault lies in the valley at the junction of the Cannon and Straight rivers. The depth of the valley here as compared with that at Owatonna is noteworthy. Much of the city is built on a terrace of alluvial material deposited by the Straight River at a higher stage, but part of the city lies on the bluffs on either side of the valley. Those on the east side rise fully two hundred feet above the level of the river. Faribault is the county seat. It was named in honor of Alexander Faribault, eldest son of Jean Baptiste Faribault, an early trader in Minnesota. Alexander came to the Cannon River country to trade with the Indians in 1826 and persuaded a band of Sioux to move to the site of the city in 1834.

Faribault
Population 11,089
Elevation 1003 feet



HIGHWAY NO. 1 THROUGH RICE AND DAKOTA COUNTIES. THE HIGHWAY IS INDICATED BY A HEAVY BLACK LINE

The city is the site of many schools, including Shattuck Military Academy, St. Mary's School, and Seabury Divinity School, all established by Bishop Whipple, an early Episcopal missionary in the region. The above schools, together with the state schools for the deaf, blind, and feebleminded, are located along the east bluff of the river. The city is served by the Rock Island; Chicago, Milwaukee and St. Paul; and Great Western railways, and is a manufacturing center. Within a distance of from three to ten miles west of the city is a group of ten lakes with many resorts. A special folder issued by the Faribault Chamber of Commerce may be obtained describing the points of interest in and near the city.

Geology at Faribault.—Here one sees the first topography in which glacial deposits fail to mask the underlying rocks. Along the east side of the Straight River a prominent bluff exposes many outcrops of the St. Peter sandstone, a white, sugary, pure quartz rock. This may be seen best at the Third Avenue bridge near the post-office. (See Plate III-A.) About eighty feet of this rock is exposed. Above, but less well exposed, are the Decorah shale and the Platteville limestone. The Platteville limestone is quarried about two miles southwest of town. The pronounced valley of the region is a result of the resistance to erosion of the solid rock, which forced the river to work in a comparatively narrow trench. Exposures on the west side of the valley are limited because of a lack of recent erosion on that side. However, at the tourist camp on the bluff at the southwest edge of town an old quarry exposes the Platteville limestone and the St. Peter sandstone.

A drive through the school grounds and out Highway No. 21 (see Route Map No. 2) shows that the schools are not on the highest part of the valley side, but are on a comparatively level area, or terrace along the river. This terrace was probably formed by erosion along the top of the resistant Platteville limestone. The area to the east is notably hilly, due to strong terminal moraine deposits crossing the region from north to south. From a point on this high land one overlooks the valleys of the Straight and Cannon rivers and the insignificance of the present streams as compared with the size of the valleys is evident.
This is a common feature of glaciated regions, a result of the large amounts of water derived from the melting ice of the glaciers.

Highway No. 1 passes over the Cannon River near the north edge of town, where a dam furnishes power for woolen mills. Continuing northward, outcrops of sandstone may be seen along the east bluff of the river and also at the roadside at a corner a mile north of the bridge. Beyond this the road turns north again and leaves the valley, and passes over undulating moraine country. High gravel ridges and knobs are characteristic, but the St. Peter sandstone is exposed in the road cuts. A big bend in the river brings it back to the road a few miles north and there the valley is wide and shallow. Six miles north of Faribault the road turns east and at Bridgewater crosses a long ridge which consists of stratified gravel as shown in the road cut. This is known as the Bridgewater esker (see page 20), a more or less continuous ridge extending nearly five miles north and south. The ridge rises at places to a height of seventy-five feet but is not very regular. The rounded pebbles of the gravel show that it was deposited by water probably in a channel beneath the ice. As the ice retreated the gravel, washed more or less free from silt, was left to mark the old channel. The Cannon River has since cut through the ridge.

The valley of the Cannon River is followed north to Dundas, where the road crosses to the east side of the river. It follows the east side to Northfield.

Northfield
Population 5544
Elevation 910 feet

Northfield was platted in 1855 and is said to have been named for two of the founders, John W. North and Ira Stratton Field. The town is known as the "College City" from the fact that two large colleges are located in the city. These are on opposite sides of the river, Carleton on the east side and St. Olaf on the west. The town is served by four railways.

A few rock exposures are found in the valley, and foundations for buildings at the college of St. Olaf are in limestone and sandstone of the Platteville and St. Peter formations. The Shakopee dolomite which lies below the St. Peter is exposed on the edge of the Carleton football field.

Highway No. 1 crosses the river in Northfield and follows the valley to a point a mile north of the city where the river turns sharply east near the Dakota county line.

The geology of Rice County may be summarized as follows: The numerous exposures of bedrock along the valleys of the Straight and Cannon rivers which have been noted in the descriptions of the route, represent five formations of the Ordovician, beginning with the Shakopee dolomite as the lowest and including the St. Peter sandstone, Platteville limestone, Decorah shale, and Galena limestone. The Shakopee dolomite is found in the northern part of the county and the others more or less in order from north to south.

The glacial drift of the western part of the county consists largely of terminal moraine. East of the Straight and Cannon rivers is a belt of old gray drift (see page 19) which consists principally of clay and is a deposit of a glacier which preceded the one which covered most of the area seen thus far. Small areas of outwash along the rivers complete the list of deposits.

DAKOTA COUNTY

(Total area 611.3 square miles; covered by water 5.45 square miles)

Dakota County was established in October, 1849, and was named for the Dakota Indians, a group of tribes originally occupying much of Minnesota and adjoining states.

Highway No. 1 enters the county along the valley of the Cannon River which turns eastward just north of the county line and flows to the Mississippi. Where the road leaves the river the Shakopee dolomite outcrops in the road cut. To the north the country is nearly level and was originally prairie. At Castle Rock station, which is a short distance west of the highway, the land is higher and it continues to rise to the north. The road cuts expose St. Peter sandstone and about one-half mile east of the road glimpses may be had of the remains of Castle Rock.

Castle Rock.—This is an isolated shaft of St. Peter sandstone left by the erosion or wearing away of the surrounding material. It was originally forty-five feet high and was an Indian landmark for untold centuries. Nicollet and other early explorers mention it in their writings. The upper part has now fallen, due to the action of the weather, so it is no longer such a prominent feature of the landscape.

It is noticeable at once in passing through the higher country north of Castle Rock that the trees are more numerous and some areas have not been cleared. The soil is somewhat sandy due to the inclusion of considerable amounts of the sandstone in the glacial drift.

Near Farmington the country is somewhat lower and very level. This area is an extensive prairie formed by outwash material which extends east to the Mississippi River and has a width at places of twelve miles. The outwash lies to the south of a pronounced terminal moraine and it was probably derived from the ice front at that location. (See Chapter II.)

Farmington
Population 1449
Elevation 900 feet

Farmington is a railway junction point and a distributing center for the fine farming country surrounding it. State Highway No. 50 branches off from No. 1 here and furnishes a shorter route to Minneapolis than No. 1, which passes through St. Paul.

Beyond Farmington and continuing to Rosemount, is the level outwash area noted above. Just north of Rosemount the country becomes very hilly and there are many sharp knobs and undrained depressions. These are the typical features of a well-developed terminal moraine and represent a long continued heaping up of débris by the melting ice. The moraine continues to the Mississippi River. This area was originally timbered and some of the hilly portions remain uncleared. Oaks are the prevailing trees, but poplar, birch, and others also are found. There are many small lakes occupying the depressions formed by the drift blocking the drainage channels, a typical feature of glaciated country. About two miles north of Westcott a new road has been constructed to cross the Minnesota River at Mendota and Fort Snelling and to enter Minneapolis on the west side of the Mississippi. From the high points along the road beyond Westcott the cathedral dome in St. Paul may be seen directly ahead.

It has been noted that the St. Peter sandstone outcrops along the highway in Dakota County, but these exposures are small and give little idea of the nature of the rock. Along the Minnesota and Mississippi River gorges there are excellent outcrops not only of this formation but in addition of the Jordan sandstone, Oneota dolomite, Shakopee dolomite, which are stratigraphically below it, and the Platteville limestone, Decorah shale, and Galena limestone above. Detailed discussions of these formations may be found in the various publications of the Minnesota Geological Survey.

The cover of glacial drift which is found over much of Dakota County is rather variable. The southern portion near Castle Rock is composed of old gray drift which has been previously mentioned in the description of Rice County (page 30). The large area of outwash material in the region around Farmington and extending eastward to the Mississippi River has been noted. North of Rosemount and extending the entire width of the county from east to west is a well-developed terminal moraine. In the western part of the county are small areas of ground moraine, terminal moraine, and old gray drift. In general the relief of the surface is pronounced especially in the region near the rivers.

CHAPTER IV

THE TWIN CITY REGION[1]

The cities of St. Paul and Minneapolis are located in Ramsey and Hennepin counties, respectively.

RAMSEY COUNTY

(Total area 187.15 square miles; covered by water 13.45 square miles)

Ramsey County, with the exception of a part of the city of St. Paul, lies on the east side of the Mississippi River and below the mouth of the Minnesota. It is the smallest county in the state, but embraces St. Paul, the capital. The county was established October 27, 1849, and was named in honor of Alexander Ramsey, the first governor of Minnesota Territory. The county was one of the nine original counties and contained a much larger area, but in 1857 it was reduced to its present size.

HENNEPIN COUNTY

(Total area 605.8 square miles; covered by water 13.45 square miles)

Hennepin County lies north of the Minnesota River and west of the Mississippi River, excepting a small area at St. Anthony falls which lies east of the Mississippi. The county was named for Louis Hennepin, the Franciscan missionary and explorer, who, with Pickard du Gay, first visited the region in 1678.

The traveler following Highway No. 1 northward from the southern part of Minnesota may enter the Twin Cities, as Minneapolis and St. Paul are known, by any one of three routes. Highway No. 1 may be followed practically due north to St. Paul, part of which lies south of the Mississippi River. The main part of the city is reached by passing over the "High Bridge." If Minneapolis is the destination it may be reached from St. Paul by several streets connecting the two cities, or by following Highway No. 50 west and north from Farmington and entering the city on Lyndale Avenue. An alternative is provided by the new cut-off just north of Westcott. This route enters Minneapolis over a new bridge across the Minnesota River from Mendota to Fort Snelling, and takes the traveler directly past the large tourist camp at Minnehaha Park.

The Twin Cities form one of the most important metropolitan centers in the West. The United States Census Bureau on July 1, 1924, estimated the population of Minneapolis to be 417,280 and that of St. Paul to be 243,946. The main business sections of the cities are about ten miles apart, but the area between is built up along the principal connecting streets. Both cities provide information bureaus and camp grounds for tourists and everything practicable is done to help the traveler.

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[1] Map No. 3 shows the region on a scale ⅜-inch to the mile.

St. Paul was located at the head of navigation on the Mississippi Rive and it was there that the cargoes were broken up and distributed. Thu the city received its first impetus. Minneapolis grew up around the powe sites at the Falls of St. Anthony.

ST. PAUL

St. Paul is one of the oldest settlements in the state and was mad the capital of the territory when it was first organized. The site was fir settled by Pierre Parrant in 1838, and the name was taken from the littl Catholic chapel built in 1841 under the direction of Father Lucian Galtie St. Paul soon became the largest settlement in the state, but its populatio was eventually exceeded by that of Minneapolis. The settlement was organized as a village November 1, 1849, and as a city March 4, 1854. Th area within the city limits has grown by repeated additions to 55.44 squar miles, all situated within Ramsey County. The city is partly bounde on the south and west by the Mississippi River which makes a big S-shape curve in this area. An excellent boulevard drive follows the river abov Fort Snelling.

In addition to being the capital of the state, St. Paul is an importan railway center with ten systems radiating from it, and the city is an important manufacturing center for a great many products. Wholesal houses are important supply centers for the Northwest. Visitors' guide with information as to places of interest are distributed by the St. Pau Association. Places worthy of a visit include: the State Capitol, Centra School of Agriculture and University Farm, Hamline University, Macalester College, St. Thomas College and St. Paul's Seminary, the Ford plan and government dam, fish hatchery, River Boulevard and Summit Avenue the fine residence street, and Mounds Park. One of the most interestin places in St. Paul is the Minnesota Historical Building on the capit grounds. The museum in this building contains a great many interestin educational exhibits. A large library is also maintained.

MINNEAPOLIS

The first settlement within the area of the present city was establishe in 1849 near the Falls of St. Anthony on the Mississippi. A village name St. Anthony was platted on the east side of the river. The first hous on the west bank was built by Colonel John H. Stevens in 1849. Upham in his book on *Minnesota Geographic Names,* gives the following note on the origin of the name. "The earliest announcement and recommendation of this name was made by Charles Hoag to the editor of the *St. Anthony Express,* George D. Bowman, on the day of publication, November 5, 1852." "Soon this new name, compounded from Minnehah and the Greek 'polis' for city, displaced the earlier names." The city wa

incorporated March 2, 1866. At present it covers 53.29 square miles and includes six large natural lakes within its limits. The Mississippi River flows diagonally through the city from northwest to southeast and this channel, together with the system of lakes, makes the site one of great natural beauty. Minneapolis leads the world in the flour milling industry, with mills having a daily capacity of 95,300 barrels. It is a manufacturing and wholesaling center with an annual output of over $1,000,000,000. The. Civic and Commerce Association maintains a tourist bureau which supplies information regarding the city. Points of interest include the milling district, the larger of 127 parks, Victory Memorial Drive, river boulevards, University of Minnesota, Minnehaha Falls, the six lakes, Fort Snelling, and Lake Minnetonka, the summer residence center west of the city.

FORT SNELLING[2]

In July, 1805, First Lieutenant Zebulon M. Pike of the United States Army, was sent up the Mississippi River from St. Louis to explore the region to the north and to gather data regarding the Indians and in addition to obtain land for military and trading posts. On September 22, 1805, he arranged a treaty with a party of Sioux warriors granting to the United States, for the establishment of a military post, an area of land nine miles wide on each side of the river, and extending from the mouth of the St. Peter's, as the Minnesota River was then called, up to the Falls of St. Anthony.

It was not until 1819 that the first troops were sent to the site. In that year Lieutenant Colonel Henry Leavenworth was sent out in command of an expedition from Detroit, Michigan, with orders to establish a military post at the mouth of the St. Peter's River. The place was reached on August 24, and a temporary camp was constructed near the present site of Mendota. Early in 1820 Colonel Leavenworth began the construction of a fort near the present site between the Mississippi and the Minnesota and across the Minnesota from the original camp. The summer camp was known as Camp Coldwater and was located near a cold spring on the west bank of the Mississippi and some distance north of the present site. In August Colonel Josiah Snelling relieved Colonel Leavenworth of command and he remained for seven years. Colonel Snelling changed the site to its present position and began the construction of a fort with vigor. Major General Winfield Scott visited the fort in 1824 and was so impressed by the colonel's efficiency that he recommended that the name be changed from Fort St. Anthony to Fort Snelling. For many years the fort was the principal point above Prairie du Chien. The reservation as first outlined included much of the area now covered by the cities of Minneapolis and St. Paul. It was much reduced in 1852 and again in 1871. It was the main mustering point for the Minnesota regiments in the Civil War and headquarters for the operations incident to the Sioux outbreak of 1862. During the World War it was the location of a large officers' training camp. It is now occupied by a considerable body of the regular army troops, and each summer a number of men are trained there for the organized reserves.

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[2] For a detailed account of the establishment of the fort, see Folwell, W. W., A history of Minnesota, vol. 1.

GEOLOGY AND PHYSIOGRAPHY ALONG THE MISSISSIPPI RIVER IN THE TWIN CITIES

The most interesting geological features of the Twin City region are exposed along the Mississippi River from St. Paul up through Minneapolis. If but a limited time is available a trip by auto up one side of the river and down the other will cover more points of interest than any other that might be outlined.

The Mississippi River is first seen by the traveler entering the area from the south on Highway No. 1 at the "High Bridge" in St. Paul. This is an excellent place from which to view the gorge and much of the city as well. The gorge is over 200 feet deep and a half mile wide. The bridge is much higher at the south than at the north end, due to a broad rock terrace on the south side about 80 feet above the river. This terrace extends back from one-half to one mile and is marked by a line of bluffs which rise fully 100 feet to the general level of the country. A striking feature which may be observed from the bridge is the narrowness of the present stream as compared with its gorge. This, as has been explained in Chapter II, is a result of the large stream which flowed in the valley when the ice front retreated to the northern part of the state. The gorge is partly cut through beds of solid rock. The St. Peter sandstone forms prominent white cliffs just above the water level and below the terrace described above. On the south side of the river below the bridge many caves excavated in the soft, sugary sandstone are used for mushroom culture. The south bluff being much higher naturally exposes more rock.

The Twin City Brick Company's plant about one-half mile above the bridge on the south side of the gorge utilizes parts of the Decorah shale for brick-making. The quarry exposes the St. Peter sandstone, Platteville limestone, Decorah shale, and the Glacial drift. (See page 10.) The shale pits of this plant expose many fine fossils of Ordovician age. (See Plate I.) This is perhaps the best place in the cities to see and collect these remains. Some rocks are literally filled with fossil shells.

To follow the river up to Minneapolis the markings on Highway No. 52 on West Seventh Street serve as a guide as far as Fort Snelling. This street is crossed by Highway No. 1 two blocks from the bridge. For some distance the route remains within the built-up portion of St. Paul. A broad strip of level land forms the terrace noted above and this is bounded on the north by a bluff. The width of the terrace varies from a half mile at the bridge to nearly a mile at the edge of the city and then narrows to less than a quarter of a mile just east of Fort Snelling. Above the fort the terrace is less marked, although at places it is a block or two wide, as near the Shriners' Hospital in Minneapolis. Not only are the terraces less marked above the junction of the Minnesota and Mississippi rivers at Fort Snelling, but it is noteworthy that the Minnesota occupies a broad valley. At some places it is nearly two miles wide, and it is much wider than the gorge of the Mississippi. In general a large stream occupies a larger valley than a small stream, but the opposite is true at this point. The explanation of the large valley occupied by the Minnesota may be seen on Figure 3 which shows that during the Glacial period the valley of the Minnesota was occupied by the glacial river Warren which had its source in the glacial Lake Agassiz, and doubtless a very large amount of water flowed down this outlet. (See page 21.) The narrow gorge of the Mississippi River above Fort Snelling has been formed since the ice melted by the retreat of St. Anthony Falls from the fort up to their present location.

As the traveler continues out West Seventh Street the area that has been built up is passed and a better view of the river valley to the left may be had. Shiely's quarry is located near the river a short distance from the last houses. Across the river from this point rocks may be seen outcropping more or less continuously and showing distinct layers, the St. Peter sandstone at the base, overlain by the Platteville limestone. A thin shale bed between these formations is eroded back, leaving the limestone overhanging to some extent. Excavations show that the Platteville limestone also underlies the terrace on the north side of the river, and doubtless the limestone is in part responsible for the existence of the terrace. When the river had cut down to the limestone it encountered a pavement-like floor with the result that the waters tended to cut from side to side into the soft Decorah shale rather than vertically in the resistant limestone. The Platteville limestone, however, was eroded at its lower edge downstream and the underlying soft sandstone being easily cut away, a cataract was formed which gradually migrated up past the site of St. Paul leaving a deep gorge which has since been partly filled, resulting in present conditions. Wherever the Platteville limestone is well exposed, fossil remains may usually be seen, often in abundance. This is particularly true of the upper layers. (See Plate I for illustrations of these remains.) The St. Peter sandstone is lacking in fossils throughout most of its extent, but the few remains found in it have come from the

Twin City region, particularly in those exposures along the river near South St. Paul.

At Fort Snelling a bridge crosses the Mississippi and affords an excellent view. The Minnesota River empties into the Mississippi a short distance below the bridge. At the bridge the Mississippi abruptly changes its course from a southeast direction to northeast. Pike Island is located in the Minnesota at its mouth and across is Mendota, the earliest settlement in the region. Here the Sibley house, the first stone structure in Minnesota, is preserved as a museum.

From the fort the traveler will find it convenient to continue up the east side of the Mississippi gorge. A short distance up stream from the fort, on the St. Paul side of the river, the Ford plant occupies a large area and utilizes the power from the government dam across the Mississippi at that point. Outcrops of St. Peter sandstone and of the Platteville limestone may be seen at many places along the gorge and a considerable amount of limestone was quarried out just above the dam for its construction.

Upstream on the St. Paul side, St. Paul's Seminary is situated on the river bank and still farther up is the Lake Street bridge, one of the main connecting links between the cities. Another bridge is being constructed at the Ford plant. A short distance north of the Lake Street bridge is the line between the two cities. The Chicago, Milwaukee and St. Paul Railway bridge crosses the river just beyond the boundary line. The Shriners' Hospital for Crippled Children is located on the river bank at this point. The Franklin Avenue, or Cappelen Memorial bridge, is a short distance farther upstream. This bridge is constructed entirely of reinforced concrete and has the longest concrete arch in the world. Still farther upstream the University of Minnesota occupies a large tract on the east bank from a point just below St. Anthony Falls downstream. From the campus a fine view may be had across to the power plants and flour mills grouped around the dams at the falls.

St. Anthony Falls were named by Father Hennepin, a member of the first white party to ascend the Mississippi to their location. At that time the falls afforded a splendid sight, but the water has now been directed to power purposes and dams hold back the water from the natural fall.[3] There are, however, interesting physiographic and geologic problems connected with these falls. (See Sardeson, F. W., *U. S. Geol. Survey Folio*, No. 201.) It is known from the writings of Hennepin that the falls in 1680 were located just above the site of the Tenth Avenue bridge, and later explorers locate them at various other points. The falls are formed by the river plunging over the nearly horizontal Platteville limestone and undercutting the soft St. Peter sandstone beneath. This process was started when the Mississippi sought a new channel following the retreat of the ice sheet. The falls long ago were situated at the junction of the Mississippi River with the Minnesota River below Fort Snelling and gradually worked back to their present location, leaving the conspicuous gorge noted above. Had the process continued but a short time longer, the falls would have ceased to exist. The reason for this is shown in Figure 5.

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[3] For several excellent views as well as maps and an extended discussion of the falls, see Winchell, N. H., Final report on the geology of Minnesota, vol. 4.

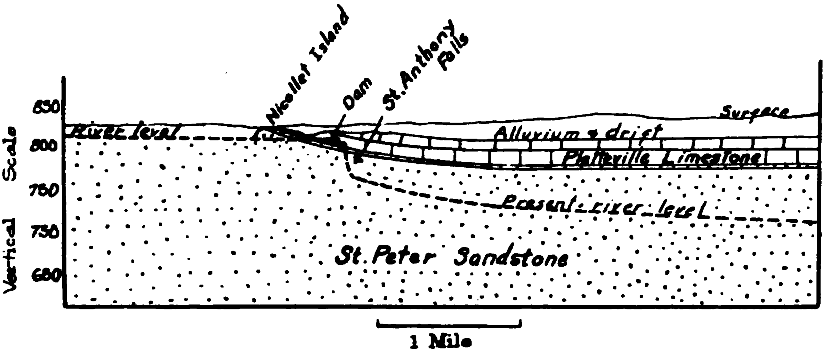

FIGURE 5. CROSS SECTION ALONG THE MISSISSIPPI RIVER NEAR ST. ANTHONY FALLS. SHOWS THE DIP OF THE PLATTEVILLE LIMESTONE WHICH BRINGS IT ABOVE THE RIVER LEVEL AT THE WEST END OF NICOLLET ISLAND. AFTER WINCHELL, SARDESON, AND OTHERS

It has been explained that the falls were formed by the river undercutting the Platteville limestone. The limestone in the region of the present falls has a slight dip to the southeast so that on the upper end of Nicollet Island just upstream the limestone is above the river level, and if the falls had reached that point there would have been no resistant bed to maintain the cliff and the falls would have degenerated into rapids. The power companies have taken proper means to stop the migration, thus maintaining present conditions indefinitely.

The river may be crossed at either Washington Avenue or Franklin Avenue and the West River Boulevard followed southward to Minnehaha Park. At the north side of the park the road swings sharply to the west and crosses an abandoned channel of the Mississippi just above an abandoned falls. The Mississippi occupied this channel as well as the main channel to the east, following the last retreat of the glacier. The present location of the tourist park and Soldiers Home was then an island (see Figure 6), but erosion was more rapid in the main (east) channel and the falls there receded more rapidly for that reason; eventually the falls passed the point where the channel divided and then all of the water followed the lower gorge, and the west channel was drained, leaving the falls of Deer Park dry.

Minnehaha Falls are located in the park where Minnehaha Creek plunges over the Platteville limestone into a gorge cut principally in the St. Peter sandstone. It is the undercutting of the soft sandstone that causes the limestone to break off with a vertical face, thus maintaining the falls. The distance from the broad abandoned channel of the Mississippi up the narrow gorge of the creek represents the distance Minnehaha Falls have receded since the falls of the Mississippi passed the mouth of the creek gorge.[4]

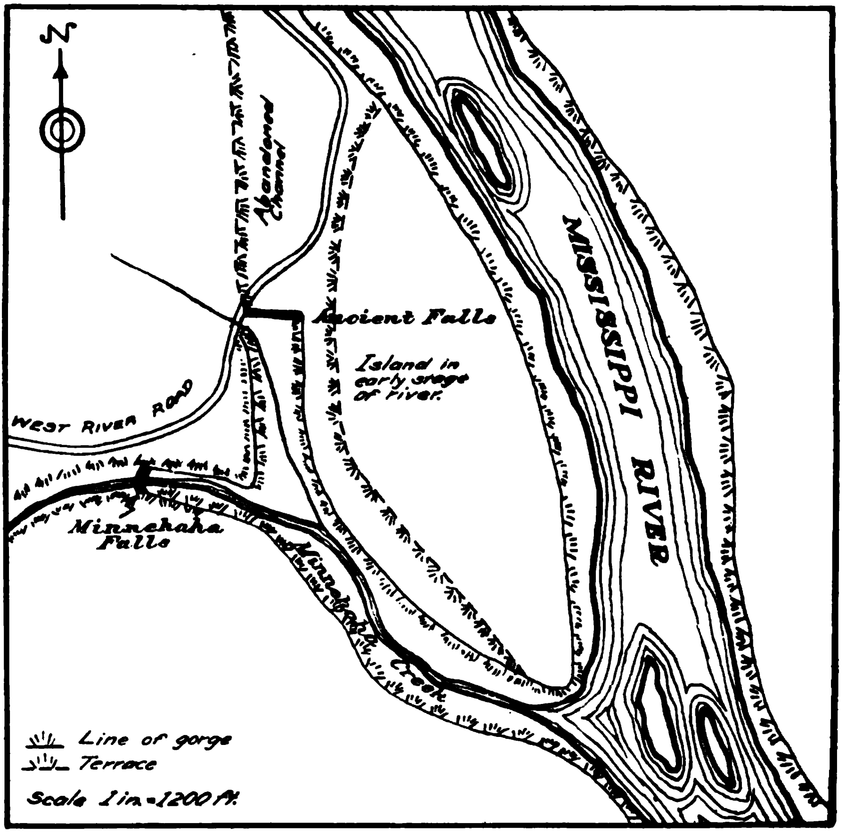

FIGURE 6. SKETCH MAP SHOWING THE RELATION OF MINNEHAHA FALLS TO THE PRESENT MISSISSIPPI RIVER AND AN ABANDONED CHANNEL AND FALLS OF AN EARLIER STAGE OF THE MISSISSIPPI. AFTER GRANT

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[4] For a more detailed discussion see Grant, U. S., American Geologist, vol. 6, p. 182.

Minnehaha Falls are widely known because the region around them was utilized by Longfellow as a setting for the poem *Hiawatha*. During the wet season they present a beautiful sight but they dwindle to almost nothing in dry seasons. The Minneapolis Park Board is taking steps to provide a contsant flow of water to preserve their beauty.

Preglacial river valleys of Minneapolis.—It has been noted that the Mississippi River gorge above Fort Snelling is relatively narrow and deep and has a youthful appearance as compared with the river below the mouth of the Minnesota. (See pp. 37-39.) It was recognized by the early geologists who studied the region that the present course of the river was probably not its course previous to the advent of the glaciers. Furthermore there are physiographic evidences of an old river gorge in the area between the parade grounds and Lake of the Isles. Drilling and foundation work have shown that the rock surface was deeply buried along this region. Recognizing this Mr. E. K. Soper[5] compiled all available data and published a paper describing the location of these buried valleys. The following extracts from this paper convey some idea of the main valley:

> In preglacial time the region around Minneapolis was dissected by a large river (referred to tentatively as the preglacial Mississippi), and its tributaries which cut deep valleys into the rock. . . . . . The ancient valleys became filled with glacial débris which was brought down by the ice and left behind as a thick mantle covering the entire region when the ice sheet receded to the north. Not only were the old valleys choked up with glacial drift, but the entire rock surface was buried. The depth of this drift has been determined at as many points in the city as possible, and has been found to vary from 0 to 250 feet.
>
> * * * * * * * * * *
>
> The present river follows the ancient course, which it has partially re-excavated from a point beyond the north city limits to the mouth of Basset's Creek in the north central part of the city. At this point the river leaves its preglacial channel, turns to the east and flows southeastward through a narrow gorge to Fort Snelling.
>
> * * * * * * * * * *
>
> The ancient river valley continued southward from the point where Basset's Creek now has its outlet and flowed in a broad valley with gradually sloping banks southward across the region now occupied by the chain of lakes which comprises Lake of the Isles, Lake Calhoun, and Lake Harriet. At Bryn Mawr Meadows a tributary stream joined the river from the northwest and its buried channel is now the course of Basset's Creek between Glenwood Lake and Bryn Mawr Meadows. Glenwood Lake also lies within this tributary valley.
>
> The preglacial river flowed almost due south from Lake Harriet, but no attempt has been made to outline its exact course beyond the city limits. [See Route Map No. 3.] In a general way this course can be traced for about five miles south of Minneapolis through Grass Lake, Wood Lake, and numerous small lakes and ponds.

The location of these buried river channels is of great importance in connection with building operations. Small structures do not have sufficient weight to cause settling, but for large buildings the unconsolidated material is not safe and foundations are set on piling to prevent undue settling.

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[5] Soper, E. K., The buried rock surface and the glacial river valleys of Minneapolis and vicinity: Jour. Geol., vol. 23, pp. 444-60, 1915.

Glacial deposits.—With the exception of more or less extensive areas of outwash sand and gravel along the Mississippi and Minnesota rivers, almost the entire area in and near the Twin Cities and extending west to beyond Lake Minnetonka is covered by a deposit of terminal moraine which results in the pronounced hilly surface found throughout the region. Lake Minnetonka, and most of the other lakes of the area, are due to irregular heaping up of the rock débris by the glacier.

There are two main types of material in the moraines of this area and these are known to be a result of two invasions of the ice. The older, or red drift (see Chapter II), is found in St. Paul and Minneapolis, and the younger or gray drift, in the region around Lake Minnetonka and overlying the red at places in Minneapolis. At places where excavations have been made recently the two may be seen. This is the case at the Johnson Street quarry in Northeast Minneapolis, where the drift has been stripped off to expose the Platteville limestone for quarrying operations. The so-called Kansas drift is found in excavations at places beneath the younger drifts. It is normally a stiff blue clay with a few boulders in it. The surface of the Platteville limestone beneath the drift is often polished and scratched by the glacier, but as a rule this can be observed only when recent stripping has taken place. Specimens of the striated rocks are preserved in the Geological Museum of the University of Minnesota.

Rock products of the area.—The only geologic products of economic importance obtained from the region are crushed stone, sand, gravel, and brick clay and shale. Formerly several quarries were operated along the gorge of the Mississippi River, but fortunately the Park Board of Minneapolis gained control of the land along the river and stopped the work before the beauty of the gorge was destroyed. At present quarries are operated in the Platteville limestone at the Johnson Street quarry in northeast Minneapolis and at Shiely's quarry along the Mississippi at the west edge of St. Paul. This rock was used for many buildings in the early days, but the lower stone is not suitable and its use fell off, but recently the upper layer has been utilized. It offers a very attractive material. It may be seen in the University Y.M.C.A. Building, and at least one new fraternity house on University Avenue.

Sand and gravel deposits are abundant in the glacial drift and large pits may be seen at several places in and near both cities. Sand, especially for molding purposes, is obtained from the St. Peter sandstone.

Bricks are made from the shales of the Decorah and Galena formations at the plant of the Twin City Brick Company just west of the south end of the High Bridge, in St. Paul. Several plants utilize interglacial silt and clay along the Mississippi in the northern part of Minneapolis.

CHAPTER V

HIGHWAY NO. 1 FROM THE TWIN CITIES TO DULUTH

Highway No. 1 leaves the city limits of St. Paul at Phalen Park. Continuing northward a number of ponds and swamps are passed which are located in depressions between morainic hills. Farther on the hilly nature of the surface becomes less pronounced and near the village of White Bear the country is practically level. The morainic belt trends northeastward and passes east of White Bear Lake while the road goes west of it.

White Bear Lake.—This lake is the favorite summer home region for St. Paul residents and is surrounded by villages, parks, and clubhouses. The lake is said to have been named from an old Indian legend that a white bear was killed by a brave on one of the islands and that its spirit still haunts the island and lake. The Indian name was Mahtomedi, which has been retained by one of the villages on the east shore.

The city of White Bear was settled in 1850 and incorporated as a city in 1921. It is noted as a summer resort.

White Bear
Population 2022
Elevation 941 feet

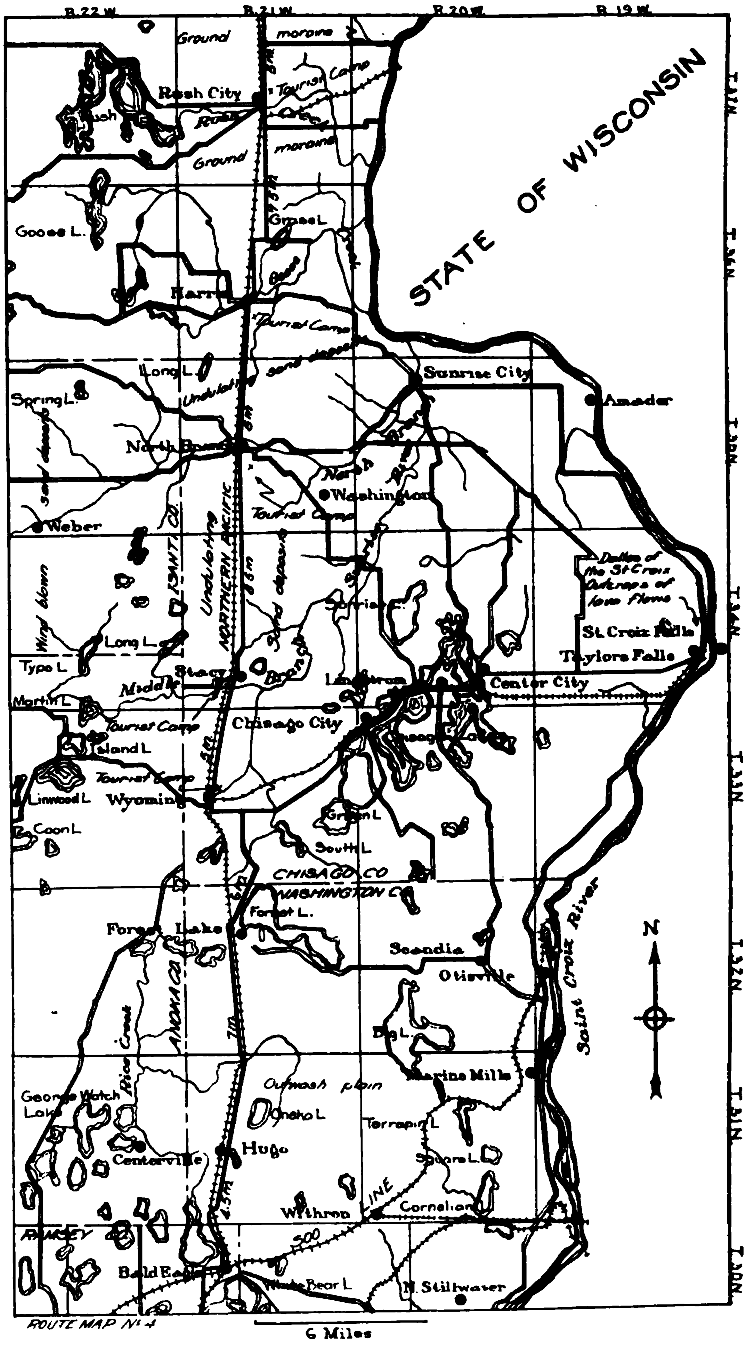
Bald Eagle Lake and the village of Bald Eagle are a short distance north of White Bear. The name was derived from a group of eagles which formerly inhabited one of the islands. Birch, Pine Tree, and Goose lakes are located near by. The soil in the region is sandy and the surface nearly level, most of the material being glacial outwash. West of Bald Eagle Lake is an extensive sand plain which crosses the highway farther north. This plain was formed by a deposit of wind blown sand over the glacial drift. This sand was probably derived from the glacial deposits before they became covered with vegetation. To the east of the road, near the north end of Bald Eagle Lake, is a small tamarack swamp. This is the farthest south that these trees may be seen along Highway No. 1, and it is the first indication of a change in the tree life which is encountered as one travels northward. (See Chapter IX.)

WASHINGTON COUNTY

(Total area 430.01 square miles; covered by water 21.14 square miles)

Hugo
Population 246
Elevation 938 feet

At the north end of Bald Eagle Lake the road passes into the northwest corner of Washington County. This was one of the nine original counties of Minnesota but is now much reduced in size, although it is 40 miles long and from 12 to 15 wide. It is bounded on the east by the St. Croix River, the boundary between Minnesota and Wisconsin. Continuing northward from Bald Eagle Lake the same type of level country extends



HIGHWAY NO. 1 FROM ST. PAUL THROUGH CHISAGO COUNTY. THE HIGHWAY AND THE SIDE TRIP TO TAYLORS FALLS ARE INDICATED BY HEAVY BLACK LINES beyond Hugo, a station on the Northern Pacific Railroad. The topography is undulating as Forest Lake is approached.

Forest Lake
Population 800
Elevation 916 feet

Forest Lake is the name of a village as well as of the lake. The lake was named from the fine wooded shores surrounding it. The village is a summer resort of some importance.

CHISAGO COUNTY

(Total area 451.66 square miles; covered by water 30.64 square miles)

A mile north of Forest Lake the Chisago County line is crossed. The county takes its name from the largest of its many fine lakes, a contraction of the Indian name Ki-chi-sago from two Chippewa words: kichi, large; and saga, fair or lovely.

The southwest corner of the county, along Highway No. 1 has the gently undulating surface of a ground moraine. A mile north of the south line the road turns westward along the shore line of an extinct lake which is marked by a marshy area. Beyond this the road trends due north to a point just south of Wyoming where Highway No. 46, a paved road, extends eastward to the Chisago lakes and Taylors Falls. (See Route Map No. 4.) Highway No. 1 turns west at this point. The region traversed by Highway No. 46 is of such interest that a side trip has been outlined to cover it. The route along Highway No. 1 is continued on page 51.

SIDE TRIP TO TAYLORS FALLS AND THE "DALLES OF THE ST. CROIX"

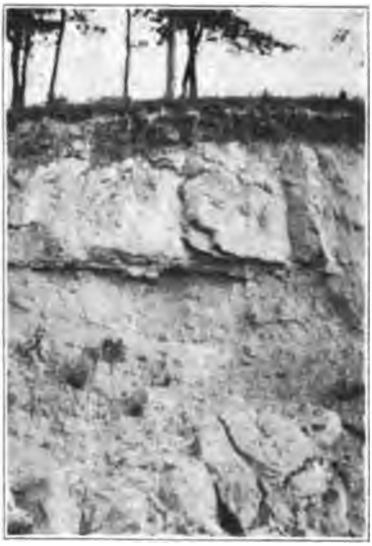
The country along the road between Wyoming and Taylors Falls cannot be surpassed for pastoral beauty and its charm is difficult to describe. The road pursues a northeasterly course for the first ten miles through the lake country.

Chisago lakes.—Green Lake is passed first, then Chisago Lake which has numerous bays and extensions both north and south of the road. Sunrise Lake lies north of Chisago Lake and north of the highway. Several smaller lakes are scattered about the surrounding country.

Chisago City
Population 422
Elevation 925 feet

The three villages, Chisago City, Lindstrom, and Center City, are situated on the lakes and on the Taylors Falls branch of the Northern Pacific Railway within a radius of about four miles. All are much utilized as resorts, and hotels, cottages, and camp sites are numerous. Center City is the county seat and received its name from its location midway between Chisago City and Taylors Falls.

Lindstrom
Population 523
Elevation 940 feet



A. EXPOSURE OF GLACIAL DRIFT IN A PIT ON HIGHWAY NO. 46. TAYLORS FALLS. THE LOWER MATERIAL IS RED DRIFT WHICH HAS BEEN SOMEWHAT MODIFIED BY WATER. ABOVE IS A MASSIVE LAYER OF YOUNG GRAY DRIFT

B. THE DALLES OF THE ST. CROIX, INTERSTATE PARK, TAYLORS FALLS

Center City
Population 1285
Elevation 901 feet

The lakes of the region are located in shallow depressions in the ground moraine and the surrounding country has enough relief to make it attractive. The shores of the lakes and the valleys of the streams are wooded. The trees are large and many fine elms, also some maples, ash, oak, and butternut attract the eye. Most of the land is cultivated and many prosperous farms are passed. This type of country continues to within a mile of Taylors Falls, where the deep, broad valley of the St. Croix River may be seen ahead and the road winds down a long steep hill to the town and river.

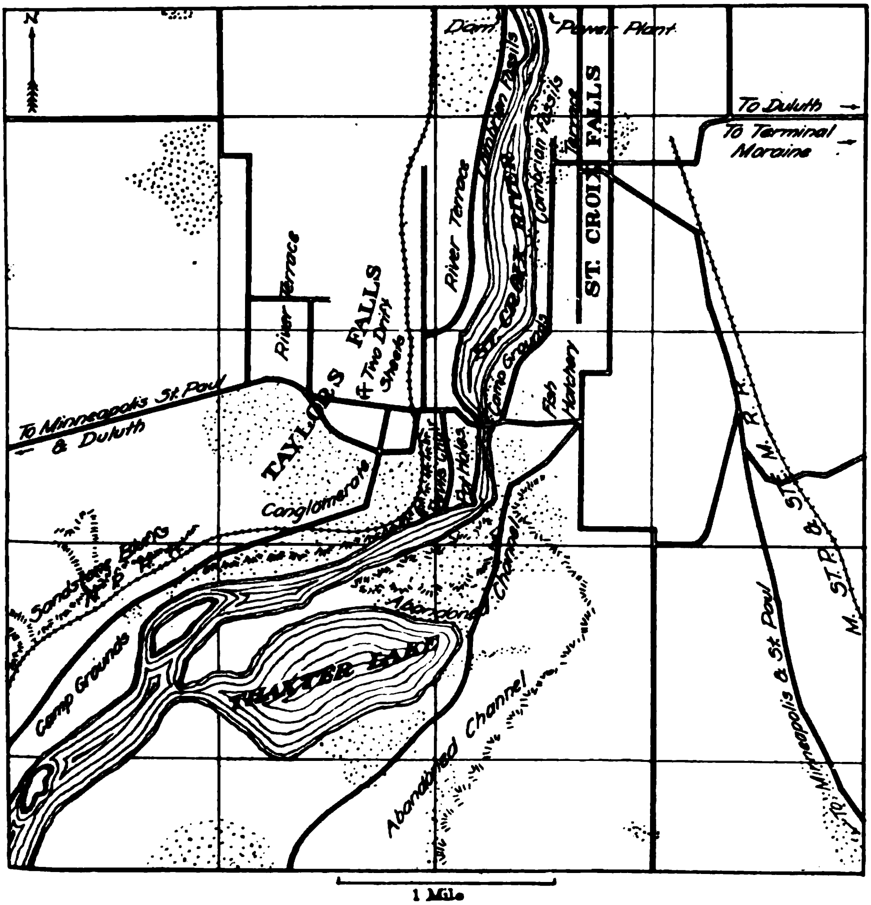


FIGURE 7. SKETCH MAP OF THE TAYLORS FALLS REGION. DOTTED AREAS INDICATE OUTCROPS OF BASALT FLOWS. AFTER BERKEY

INTERSTATE PARK AND THE "DALLES OF THE ST. CROIX"

The St. Croix (Holy Cross) River was given its name by Perrot, a French explorer, in 1689. A cross had been set at its mouth on the Mississippi, probably to mark the grave of a French trader. La Harpe in 1700 described the stream as "a great river called St. Croix because a Frenchman of that name was wrecked at its mouth." The river has its headwaters in northeastern Wisconsin and empties into the Mississippi at Hastings, Minnesota. It forms the boundary between Minnesota and Wisconsin for more than 100 miles.

The points of interest and scenery in the area about the villages of Taylors Falls, Minnesota, and St. Croix Falls, Wisconsin, led the legislatures of the two states to set aside an area of 730 acres in Wisconsin and 150 acres in Minnesota as an interstate park. The center of interest is an area of trap rock through which the St. Croix River flows in a narrow gorge. (See Plate II B and Figure 7.) One of the most attractive features is the growth of large white pines on the rocks forming the gorge. This is the farthest south that this useful species is found in Minnesota.

Taylors Falls
Population 750
Elevation 795 feet

St. Croix Falls
Population 825
Elevation 812 feet

The villages of Taylors Falls and St. Croix Falls bound the park on the north. The former is located mainly on the most extensive terrace and the latter on a higher terrace of the glacial river. St. Croix. (See Figure 3.) A dam across the river furnishes considerable power, most of which is transmitted to Minneapolis and St. Paul. Taylors Falls and St. Croix Falls were once active in logging and lumbering, but most of the forests are now cut off. A state fish hatchery is located on the St. Croix side and is supplied by large springs issuing from the side of the valley. Abundant facilities are provided for camping on both sides of the river. On the Minnesota side a beautiful area along the river just below the gorge is set aside. A more attractive spot would be difficult to find. On the Wisconsin side sites are provided along the river above the bridge.

Geology of the dalles.—The points of interest are so numerous and varied that an extended treatise would be necessary to cover them in detail. Such an article was written some years ago by C. P. Berkey, then an instructor at the University of Minnesota. His paper[1] should be consulted for a more extensive and technical treatment.

In order to understand the significance of the features that may be seen it is necessary to have in mind the geologic history of the region, as given in Chapter II, especially the parts on the Keweenawan and Glacial periods. The locations of the various points of interest are shown on a sketch map in Figure 7.

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[1] Berkey, C. P., Geology of the St. Croix dalles: Am. Geologist, vols. 20 and 21, 1897-98
———— A guide to the dalles of the St. Croix. Minneapolis, 1898.

The most prominent feature of the region is the gorge (or dalles) of the river which begins at the bridge and extends downstream for nearly a mile. The gorge cuts through a series of diabase or trap flows, exposing vertical cliffs at places over 100 feet high. The rock outcrops extend up the sides of the valley to an elevation more than 300 feet above the river. These rocks are the result of the solidification of Keweenawan lava flows which were probably poured out of great fissures somewhere to the north. Detailed work by geologists has shown that there are at least 10 flows exposed on the Taylors Falls side from the gorge up the hill beyond the schoolhouse. A thin vesicular or amygdaloidal portion marks the top of each flow, where the gases formed bubbles in the molten rock before it solidified. One block west of the schoolhouse, a volcanic ash or breccia marks an interval of explosive activity between flows.

Along the gorge practically vertical rock cliffs are most common and the reason for this may be seen in the structure of the rocks. These old lava flows are cut by extensive joint planes or fractures which cause the rock to fall off in large blocks. The principal joints are vertical, but there is also a somewhat less developed horizontal set. These joints have even affected the course of the river, causing the abrupt right angle turn. The rock at the corner is locally known as "angle rock." The devil's chair is another conspicuous result of erosion influenced by joints.

The potholes.—Perhaps the most interesting feature of the region is the series of potholes in the large area of solid trap rock exposed along the Minnesota side of the gorge between the bridge and the boat landing. The potholes are cistern-like holes varying in size from small depressions a foot across to huge wells many feet across and scores of feet deep. Glacier Kettle is the name applied to one which has recently been cleaned out and found to be 60 feet deep, 12 feet in diameter at the surface, 15 at the 42-foot level, and 3 feet in diameter at the bottom. The irregularity in diameter is accounted for by jointing and variation in the hardness of the rock. At places the walls separating a series of holes have been destroyed by erosion and a gorge has formed. These potholes have been formed by eddies in the swiftly flowing river where the swirl of the water was strong enough to rotate boulders which continued to drill downward in the exceedingly hard and tough rock until the waters ceased to flow above them. Many of these rounded boulders may be observed in the potholes or near by.

Terraces and abandoned channels.—While the river was eroding the valley down to its present position, the channel was not at all times located directly above its present position, but it followed various courses which are now marked by terraces and abandoned channels. Five more or less distinct terraces are found along the river. The highest is represented by a level area above Taylors Falls where a road runs northward. The next is best developed on the Wisconsin side at the level of the main street of St. Croix Falls. The next lower is best seen upstream from St. Croix Falls along the road which follows the river. A still lower terrace is occupied by the main part of Taylors Falls. The lowest is not widely developed, but forms small benches along the gorge just below the bridge.

An abandoned channel is found on the Wisconsin side from the elbow in the river south past Thaxter Lake (Lake of the Dalles). At a later stage the river was diverted to a channel through Thaxter Lake. (See Figure 7.) A new road has recently been built along the abandoned channel. The cliff which forms the south wall of the gorge was thus an island at an earlier stage in the development of the valley.

Cambrian rocks.—Thus far the only rocks mentioned are the lava flows, but a short distance down the railroad tracks, below the dalles, high cliffs of Franconia sandstone, a Cambrian formation, compose the valley walls. (See Figure 7.) Fossils are numerous, but not many are well preserved. The position of this sandstone with reference to the flows may be observed by following the railroad back to the hill near the schoolhouse, where a conglomerate may be seen at the road and railway crossing, and farther up the hill a fine exposure occurs where the road cuts through the rock. Here large boulders of trap compose the conglomerate, which grades upward into the Franconia sandstone, thus showing that the sandstone is younger than the flows. That the conglomerate is Cambrian is shown by the fossils it contains.

Excellent Cambrian fossils are found in outcrops of Dresbach shale on both sides of the river nearly opposite the Taylor House.

Glacial geology.—The country around Taylors Falls was of course swept by the glaciers when they crept down from the north and as a result deposits peculiar to glaciated country were left. By taking either road which trends east from St. Croix Falls, one climbs rapidly to a height of five hundred feet above the river. Here the country is extremely hilly with rounded knobs and rudely circular depressions or kettles alternating. This topography is typical of a well-developed terminal moraine, and it forms a belt about two miles wide, which trends roughly north and south through the region.

Where Minnesota Highway No. 46 descends the hill into Taylors Falls large openings for gravel have been made in the hillside and in this the glacial drift is clearly of two kinds. At the base is a red gravelly drift with more or less stratified sand and gravel in the upper part. Overlying this is a bed of gray boulder clay of a distinctly different type. (See

Plate II A.) The red drift was deposited by a glacier which advanced from the northeast and the gray drift, by a later one which advanced from the northwest. (See page 19.) The action of water stratified or modified the upper part of the red drift before the gray material was deposited above it.

HIGHWAY NO. 1

(Continued from page 45)

Wyoming
Population 253
Elevation 905 feet

Wyoming was settled in 1855 by people from Wyoming, Luzerne County, Pennsylvania. It is a supply point for the surrounding farms and a station on the Northern Pacific Railway. From Wyoming north to Stacy the country is level and the soil notably sandy, the area being part of a great sand deposit covering the drift over much of Anoka and Isanti counties, and extending into Sherburne on the west and Chisago on the east. The sand was apparently deposited by winds which swept over the barren areas when the glacier retreated and before vegetation had become established.

Stacy
Population 84
Elevation 928 feet

Stacy was established as a station on the Northern Pacific in 1875. Except for the creek valley at the village the sand plain continues unbroken to North Branch. Midway between the towns a few pine trees may be noted west of the road. The village takes its name from the creek which is the north branch of the Sunrise River. The creek has a pronounced valley, indicating a larger stream at some past time. From North Branch to Harris the surface is more undulating and the soil less sandy than that to the south.

North Branch
Population 742
Elevation 901 feet

Just north of the village the surface is decidedly more hilly due to a small belt of terminal moraine which trends northwest-southeast across the highway. Beyond the moraine and extending past Rush City, is a gently undulating to level ground moraine area with a very fertile soil.

Harris
Population 673
Elevation 904 feet

Rush City was named from the Rush River which in turn was named from the rushes found along it in low areas. Three miles north of the town the road crosses into Pine County.

Rush City
Population 971
Elevation 922 feet

A brief description of Chisago County has been given in connection with the side trip to Taylors Falls. The only rock outcrops found are along the St. Croix River and these have been described. The topography is very level except for the St. Croix Valley with its tributaries. The Chisago Lake country is in a large area of ground moraine extending from Wyoming to the river. It is bounded on the southeast and northwest by narrow belts of terminal moraine. From Wyoming to Harris the sand plain has been noted. From Harris north is an area of ground moraine except for a narrow belt of terminal moraine. A considerable outwash deposit is found along the St. Croix River in that part of the county.

PINE COUNTY

(Total area 1444.5 square miles; covered by water 24.7 square miles)

Pine County was named from the extensive forests of white and yellow (Norway) pine which once covered the region. The county is large, extending eight government townships north and south and six east and west at the north, but only three at the south, where the St. Croix swings westward.

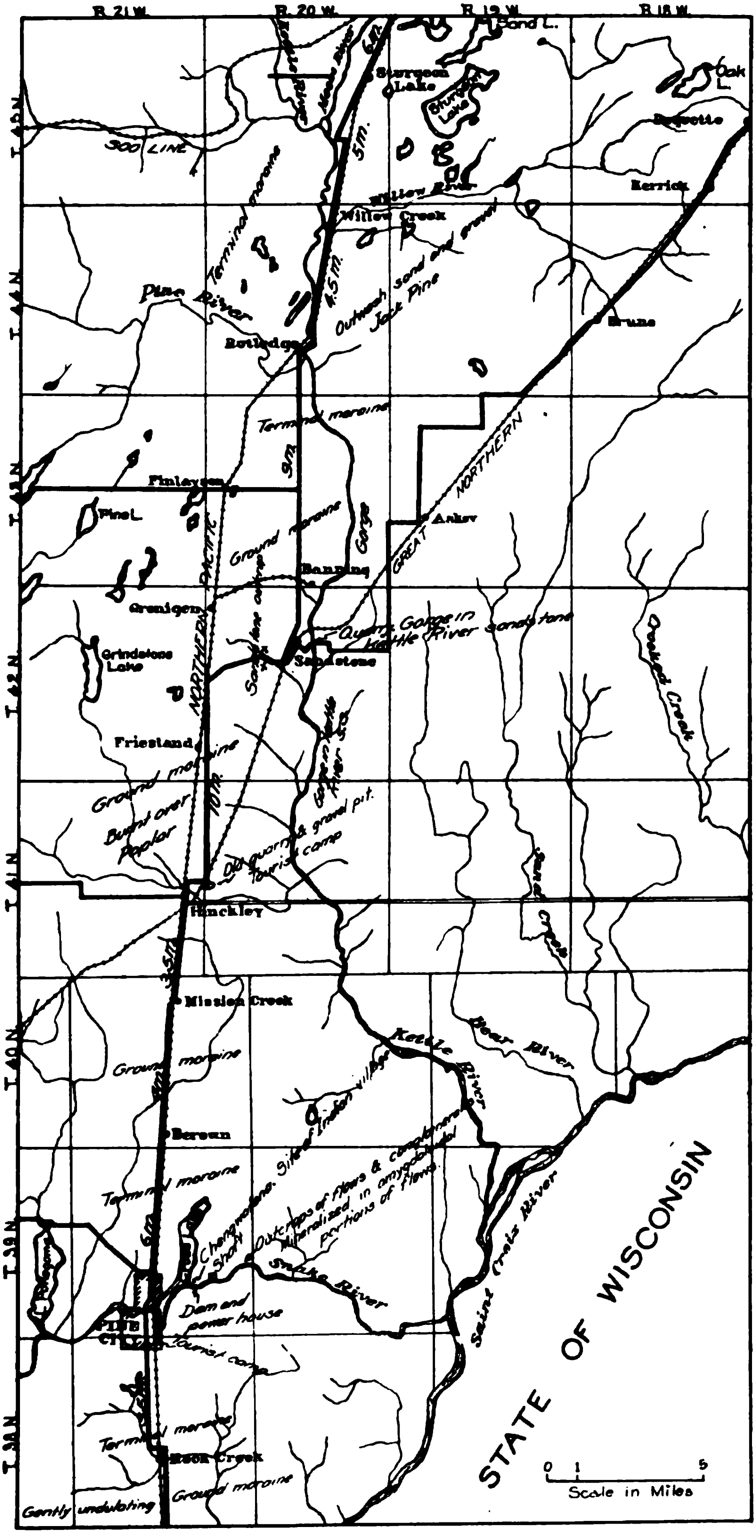
Rock Creek
Population 163
Elevation 945 feet

South of Rock Creek the surface is gently undulating but north of the town a small terminal moraine appears and there is a more rolling topography. A short distance beyond Rock Creek a few large white pines may be noted towering above the hardwood trees and from there north they become more abundant. It is also noteworthy that the hardwood trees of this region are larger than those found on the sandy belts of Chisago County. Oak, elm, ash, and basswood are common. There is little change in the topography until Pine City is reached; there a small moraine trends northeast across the county and is doubtless responsible for the two lakes of the vicinity. Cross Lake bounds the city on the east while Pokegama Lake is four miles west of town.

Pine City
Population 1303
Elevation 955 feet

Pine City received its name by a translation of Chengwatana, the name of an Indian village which had been located at the outlet of Cross Lake into Snake River. The Snake River likewise received its name by a translation of the Ojibway name Kanabec. The same is true of Cross Lake, a translation of Bemidji, a name applied by the Indians from the fact that Snake River flows in and out of, or crosses the lake. Pokegama is also an Ojibway word. Pine City is a prosperous town serving a considerable area and is a station on the Northern Pacific Railway.

Geology along Snake River.—Outcrops of solid rock are rare in the area lying north of St. Paul except along the St. Croix River. For this and other reasons a series of exposures along Snake River just east of Cross Lake are of considerable interest. A road follows the lake shore to the south of Pine City and crosses Snake River a short distance below the place where it leaves the lake. Just below the bridge is a power dam and from there downstream for two miles are numerous outcrops. These rocks are very similar to those at Taylors Falls, those on the north shore of Lake Superior, and the prevailing rocks in the Michigan copper country. (See Chapter II.) For this reason exploration for copper has



ROUTE MAP No 5

HIGHWAY NO. I THROUGH PINE COUNTY. THE HIGHWAY IS INDICATED BY A HEAVY BLACK LINE been carried on at several points, but with unsatisfactory results. Numerous outcrops may be seen for one-half mile below the power house and others occur farther down. The rock consists mostly of dense basalt or diabase flows with amygdaloidal portions representing the tops of the flows, which vary from 8 to 200 feet in thickness.

Professor C. W. Hall[2] has identified 65 lava flows and 5 conglomerate beds in this series of outcrops. The total thickness he estimates at over 4000 feet. The beds have been notably tilted from their original horizontal position and now strike north 10 degrees east and dip about 67 degrees east. At the end of the channel for the tail race one of the thick red conglomerates may be seen interbedded with the flows. A short distance farther down is another conglomerate which is not as thick. About a mile down from the bridge are two exploration shafts which followed a showing of native copper in the amygdaloidal parts of flows. The dumps show many minerals, such as calcite, laumontite, orthoclase, and native copper.

A very interesting feature of this region was brought out some years ago when a well 700 feet deep was drilled at Pine City on the west side of Cross Lake. The first 230 feet penetrated river sand and glacial drift, while the remainder was in sandstone doubtless analogous to that along the Kettle River. This shows conclusively that the lava flows end abruptly at Cross Lake. This abrupt change is no doubt a result of a large fault which has dropped the rocks west of Cross Lake with respect to those east of the lake.

North of Pine City.—Beyond the Snake River at Pine City is a gently undulating country which extends for three miles, then comes a pronounced rise with a rolling to hilly surface indicating a terminal moraine deposit. The moraine continues to Beroun, a station on the Northern Pacific Railroad. From Beroun to Hinckley the surface is level to undulating with large marshes. Some of the land is quite stony and part of it has not been cleared but is covered with a second growth of birch and poplar, characteristic trees on burnt-over land. Mission Creek is an abandoned station on the Northern Pacific Railroad, so named from a mission to the Ojibways established near there in 1838, but broken up by a war party of Sioux, May 24, 1841.

Hinckley
Population 673
Elevation 1032 feet

Hinckley was named in honor of a stockholder of the St. Paul and Duluth Railroad. It is roughly half way between St. Paul and Duluth. The village was destroyed by a disastrous forest fire which swept the region on September 1, 1894. Four hundred eighteen people perished at Hinckley unable to escape in any direction. The town was promptly rebuilt and has continued to grow.

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[2] Hall, C. W. Bull. G. S. A., vol. 12, page 314, 1901.

Between Hinckley and Sandstone the surface is undulating to level and the soil is stony. Much of the land has not been cleared, but some prosperous farms show the possibilities of the land.

Sandstone
Population 1200
Elevation 1119 feet

Sandstone was settled as a village in 1885 when quarries were opened in the sandstone outcrop along the Kettle River and quarrying remains the principal industry.

The Kettle River gorge.—The Kettle River is a small stream which enters Pine County near the northeast corner and flows southward to a point within ten miles of its mouth, where it turns eastward and empties into the St. Croix. In its upper stretches the river flows in a relatively shallow valley in glacial drift and outwash gravel; but, about two miles below Rutledge, Keweenawan sandstone is exposed and the stream has intrenched itself in this rock. The gorge becomes rapidly deeper to the south and has ragged cliffs on each side ranging from 50 to 100 feet in height. This continues to a point opposite Hinckley where the river crosses into lava flows. The gorge may be most easily seen at Sandstone by driving along the county road to the east edge of town a distance of only half a mile from Highway No. 1.

The Kettle River sandstone quarries.—A bridge crosses the river at this point and gives a good view of the gorge and the quarries which are located along the west side, mainly above the bridge. The sandstone has been quarried for a distance of 2000 feet along the river and to a height of 100 feet. The rock is used for structural purposes, paving blocks, and crushed stone for concrete. It is of a light pink or salmon color but varies near the top to a darker yellow. The rock contains no fossils but its relations to outcrops elsewhere suggest that it belongs to the Keweenawan series. Its position is above the flows. (See page 10.) The beds vary from one to six feet in thickness and have but few joints, giving a massive appearance to the quarry face. The stone is attractive on account of its light color and has been used in many buildings, among them the Library, University of Illinois; Spokane Club, Spokane, Washington; Des Moines Public Library; Great Northern Station, Minneapolis; Pillsbury Hall, University of Minnesota; courthouses at Elk Point, South Dakota, and Crookston, Grand Rapids, and Benson, Minnesota. The quarries may be reached by a road from the west end of the bridge and will be found well worth a visit.

The highway north of Sandstone.—North of Sandstone for six miles is a deposit of level to gently undulating ground moraine which is largely covered with poplar and brush. Near Rutledge is a somewhat more hilly and sandy belt of terminal moraine which is covered mainly with jack pine trees, which flourish on sandy soil.

At Rutledge the highway crosses to the east side of the Kettle River, which has a shallow valley at this point, and no rock outcrops are found. The road and railroad follow the river valley to Willow Creek and Sturgeon Lake.

Rutledge
Population 90
Elevation 1036 feet

Beyond Sturgeon Lake the soil is sandy and gravelly and the country comparatively level. The sand and gravel are well stratified and represent outwash material deposited by glacial waters. Jack pines are the prevailing trees.

The principal rock outcrops in Pine County are sandstones and lava flows of Keweenawan age. It is quite probable that a considerable portion of the county is underlain by these on the extreme northwest corner where older slates outcrop. In general the cover of glacial drift is not so thick as farther south so that outcrops have been found at various places through the county especially along the streams.

Willow Creek
Population 247
Elevation 1038 feet

The glacial drift consists principally of ground moraine with a few terminal moraines with a northeast trend across the county. Extensive areas of outwash are found along the St. Croix River in the southeast portion, and along the Kettle River in the northern part of the county.

Sturgeon Lake
Population 208
Elevation 1080 feet

CARLTON COUNTY

(Total area 867.19 square miles; covered by water 9.47 square miles)

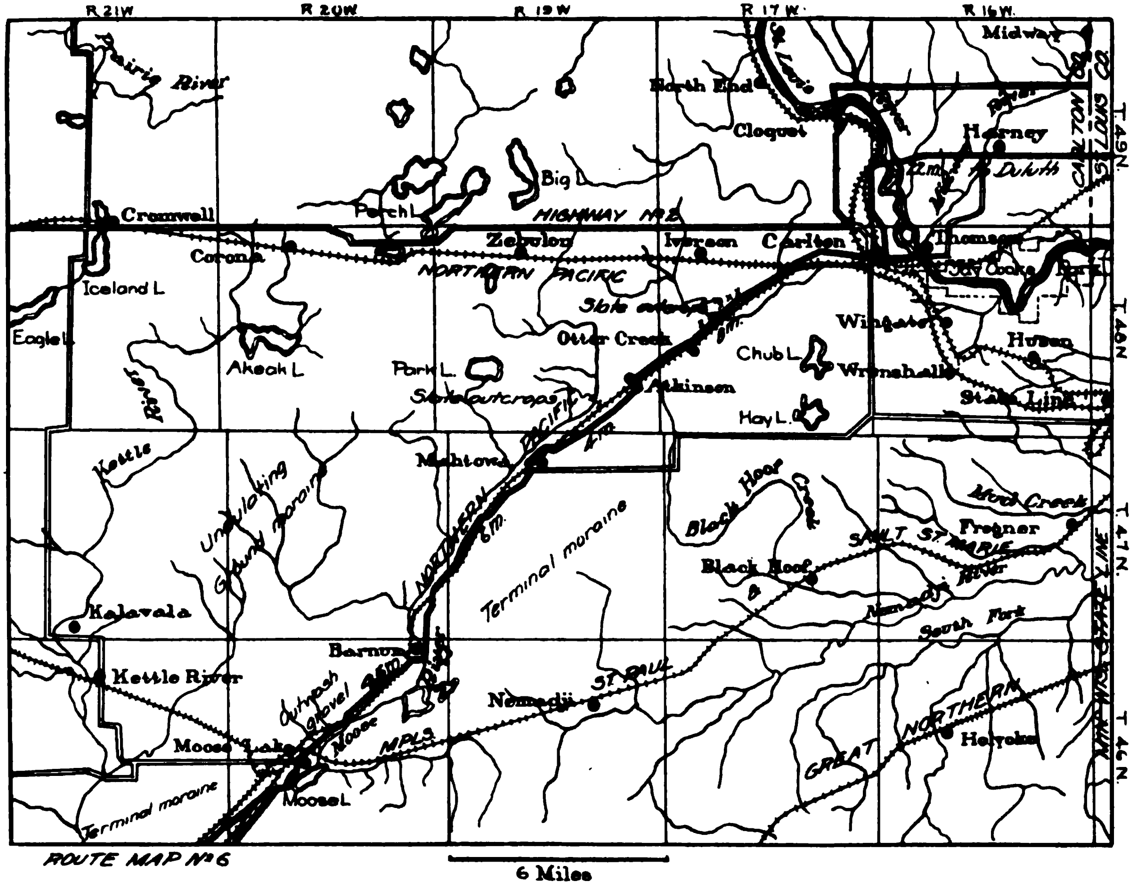
Carlton County extends six townships east and west and four north and south. It was named in honor of Reuben Carlton, an early settler.

Highway No. 1, entering the south side, follows the valley of the Moose River, which was formerly an outlet for glacial Lake Nemadji, a stage of Lake Superior when most of the present lake was filled with ice. (Another stage known as Lake Duluth is shown in Figure 4.) South of Moose Lake the valley widens and includes the lake. The south shore of the glacial Lake Nemadji follows the present shore of Moose Lake while on the north it is some distance back from the present lake.

At Moose Lake the Soo Line and Northern Pacific railroads cross. The town was entirely destroyed by the disastrous forest fire of October, 1918, in which Cloquet and several smaller towns also were practically destroyed. More than 300 people lost their lives in the catastrophe. The town was promptly rebuilt along modern lines and is now an up-to-date and thriving village.

Moose Lake
Population 571
Elevation 1065 feet

Between Moose Lake and Barnum the road follows the level country on the west side of the Moose River. Huge pits along the railroad expose the stratified gravel which underlies the valley. The deposits were laid down by the large river which occupied the valley when Lake Superior was filled by the glacier.



HIGHWAY NO. I THROUGH CARLTON COUNTY. THE HIGHWAY IS INDICATED BY A HEAVY BLACK LINE

From Barnum to Mahtowa the road continues to follow the outwash gravel terraces along the river. Mahtowa is an Ojibway word meaning bear. About a mile south of Atkinson on the west side of the railroad is a low outcrop of slate, the first exposure of this rock near the road. This slate represents the oldest rock exposed along Highway No. 1 and is of Upper Huronian age. (See page 10.) Striae or grooves formed by the scraping of the ice over the rocks are well marked on the top of the outcrop and show the movement of the ice to have been in a direction south 80 degrees west. A short distance beyond are three similar ridges all showing a rounded elongate form, due to the grinding action of the ice. The middle ridge shows especially fine glacial striae.

Barnum
Population 242
Elevation 1102 feet

Mahtowa
Population 380
Elevation 1152 feet

From this point to Carlton the same sort of rock is repeatedly exposed, especially just west of town, where there are numerous rounded, elongate ridges to which the name "roche moutonées" has been applied because they are supposed to resemble the backs of sheep lying in a pasture.

Atkinson
Population 319
Elevation 1146 feet

Carlton is the county seat and is a railroad center; several lines of the Northern Pacific and Great Northern systems radiate from it. The village of Thomson is located on the east side of the St. Louis River just beyond Carlton. Formerly Highway No. 1 crossed the river between Carlton and Thomson, but it was rerouted in 1924 over a new paved road extending north from Carlton and crossing the river about three miles to the north, and then connecting with the old route.

Carlton
Population 700
Elevation 1077 feet

JAY COOKE STATE PARK

Jay Cooke State Park consists of 3000 acres of wild rugged land on both sides of the St. Louis River extending from Thomson to Fond du Lac. (See Figure 8 for a map of the park.) The park is named in honor of Jay Cooke, a pioneer in railroad building, who secured the land along the river for power purposes. Later much of the land was found unnecessary, and in 1915, 2350 acres were donated to the state by the Cooke heirs and others have since made additions. The park auto road follows the grades of the first railroad to Duluth, now long abandoned.

The park is a game refuge, but fishing is permitted. Camp sites are numerous and are kept in condition by the state. The scenery along the river is very attractive and the geology presents many significant and important phenomena. The gorge is the most conspicuous topographic feature of the region as may be seen at the bridge between Carlton and Thomson. (See Plate III B.) A large dam just north of the

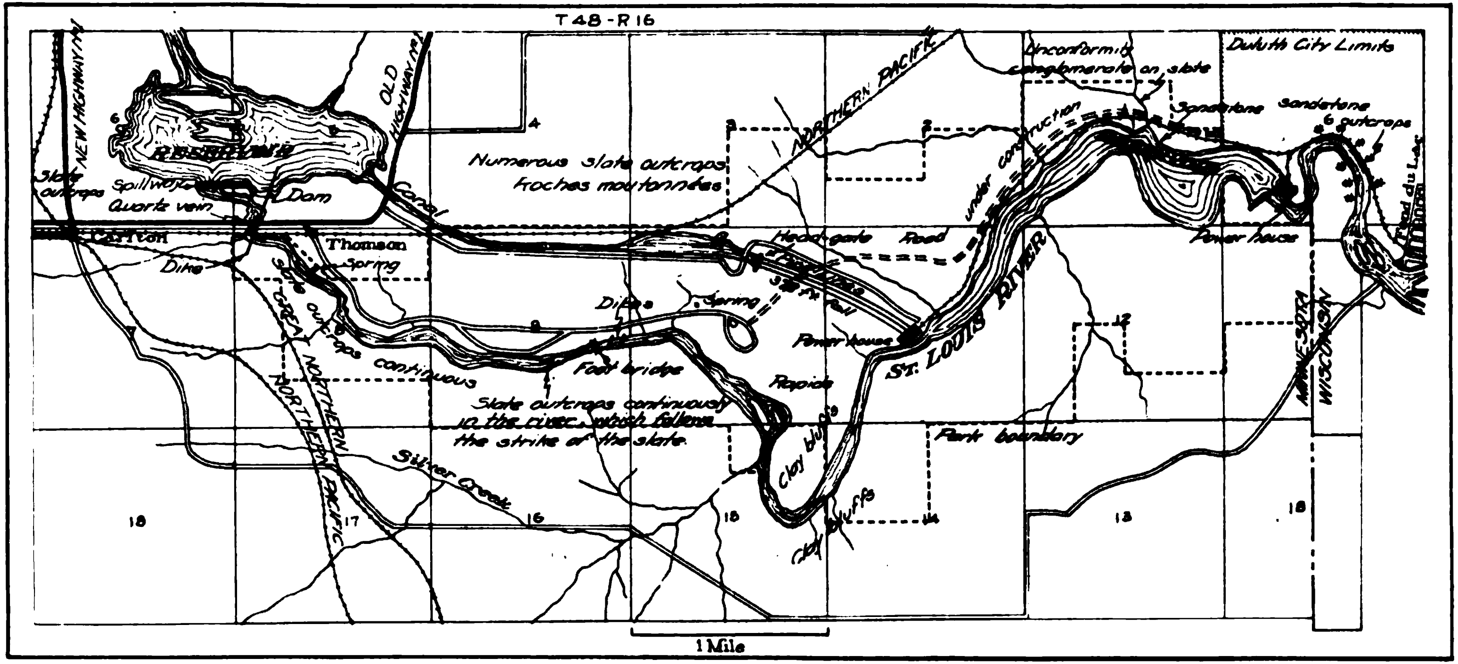
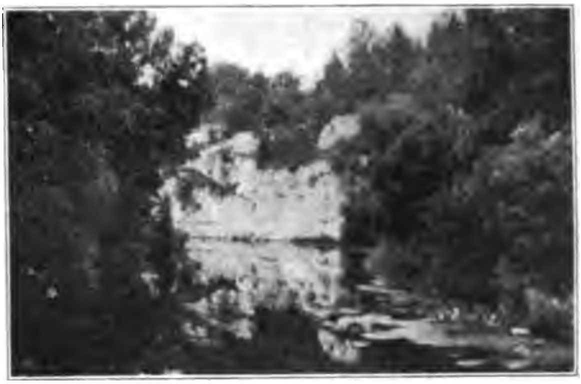
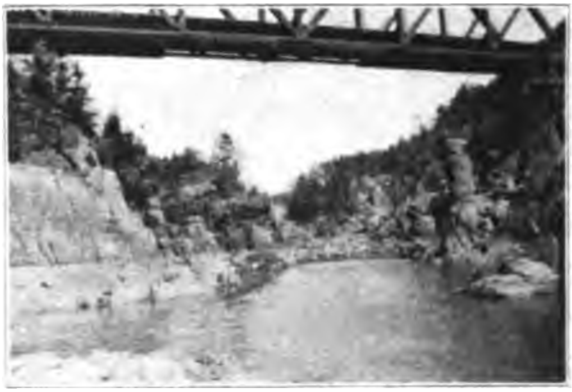


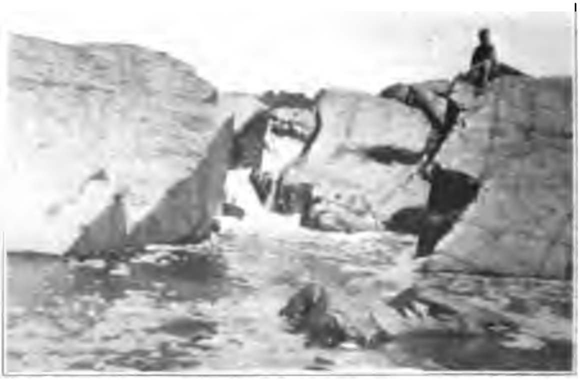
FIGURE 8. SKETCH MAP OF JAY COOKE STATE PARK AND ADJACENT AREAS ALONG THE ST. LOUIS RIVER



A. BLUFF OF ST. PETER SANDSTONE ON THE STRAIGHT RIVER, FARIBAULT



B. GORGE OF THE ST. LOUIS RIVER BETWEEN CARLTON AND THOMSON. ROCKS EXPOSED ARE CARLTON SLATE



C. BEDS OF CARLTON SLATE DIPPING TO THE SOUTH. THE WATER HAS WORN CHANNELS ACROSS THE BEDS ALONG JOINTS. ST. LOUIS RIVER, JAY COOKE STATE PARK bridge shuts off most of the water from this part of the gorge, but this only serves to expose the rocks more fully. The chief rock exposed is a slate of the same series that was noted at Carlton. Some of the layers or beds exhibit cleavage or parting and break into rhombic blocks which are as regular as if artificially cut. At places sharp folds may be observed showing that the rock was at one time under sufficient stress to cause it to bend. (See page 13.) A conspicuous feature of the slates are the holes which are formed by the weathering out of carbonate nodules or concretions. A most interesting feature is the manner in which the slate has affected the course of the river. The slate beds in general dip at an angle of 45 degrees to the south. (See Plate III C.) Erosion has resulted in a sawtooth effect at places and the water follows along the depressions for some distance. Cross joints result in narrow channels from one depression to another.

Near the center of the park in Section 10, the slate exposures end abruptly and the river flows in a broader gorge with red clay banks. No outcrops occur between this point and about the center of Section 1, a half mile above the lower power plant. There slate is overlain by conglomerate of Keweenawan age probably the base of the Kettle River sandstone. (See Chapter VI for further description.)

Formerly Highway No. 1 continued north and eastward of Thomson and Jay Cooke Park to the Cloquet road where it turned east. Outcrops of slate continue for some distance, then the area is covered with a heavy deposit of glacial drift. No conspicuous features appear until the St. Louis County line is passed. The new highway passes over country similar to that of the old route.

The most notable feature of Carlton County, especially as contrasted with the counties to the south, is the occurrence of abundant outcrops of slate. These have been noted in detail above. A large area extending eastward from Moose Lake is occupied by the deposits of glacial Lake Nemadji and glacial Lake Duluth. (See Figure 3.) Northwest of this area are the usual morainic deposits with areas of outwash gravel along the streams.

CHAPTER VI

THE DULUTH REGION[1]

ST. LOUIS COUNTY

(Total area 6503 square miles; covered by water 365 square miles)

St. Louis County is the largest county in Minnesota, and also the largest county east of the Mississippi River. It extends from Lake Superior north to Rainy Lake, a distance of 130 miles. The county is named from the St. Louis River which was probably named by Verendrye, a French explorer who visited the region in 1731 and later. The king of France conferred the Cross of St. Louis on him in recognition of his discoveries, and this doubtless accounts for the name. The county is famous for its iron mines found on the Mesabi and Vermilion ranges. Much of the northern part of the county is unsettled and is included in the Superior National Forest. Numerous lakes make much of the county a tourists' and campers' paradise.

The county is entered over Highway No. 1 about six miles northeast of Thomson. The area from Thomson to a point about two miles east of the county line is underlain by the slates, which are well exposed near Carlton. About two miles east of the county line there is a very conspicuous change in the aspect of the county. Prominent rock bluffs rise, one on each side of the road and the country is more rugged from this point to the Canadian boundary.

The first outcrops of rock are ancient Keweenawan lava flows in Section 20, T. 49 N., R. 15 W. These are related in age and character to those exposed east of Pine City and at Taylors Falls, but here they lie more nearly flat, not having been greatly disturbed since their formation. These first bluffs are of black trap rock or basalt.

The basalt lavas lie on sand and conglomerate and anyone interested in their exact relations to other formations should take short side trips from Highway No. 1.

Turning north on the west side of Section 20, T. 49 N., R. 15. W. (see Map No. 7) is a road which runs several miles and crosses outcrops of slates like those at Carlton. Running east through the center of Section 20 is a road that crosses the hill of lava. If the explorer follows the west side of this hill about a quarter of a mile north from the road he will find the lava resting on white pebbly sandstone at the base of the bluff. Within 200 yards west of the bluff outcrops of slate are visible in the fields.

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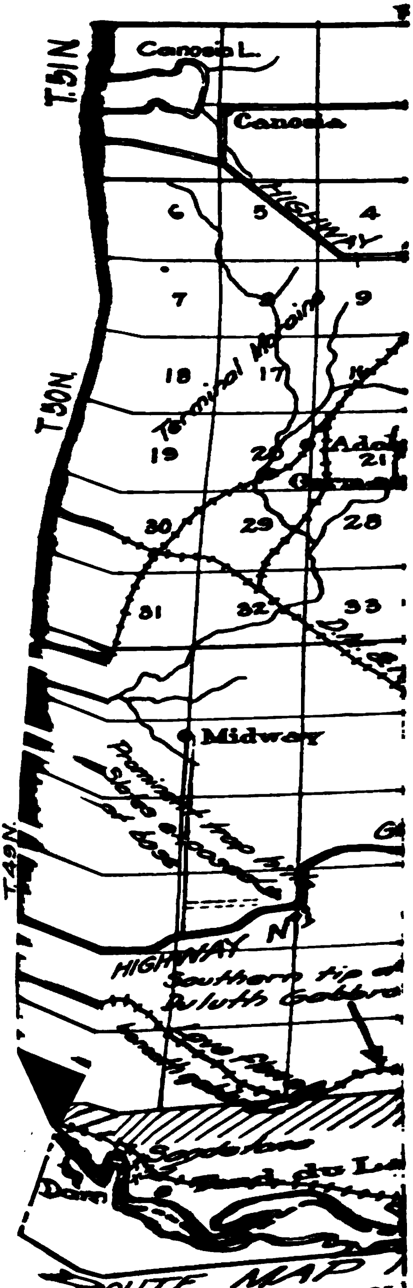
[1] See Route Map No. 7 for the city and surrounding area.



ROUTE MAP

THE DULUTH REGION.

Beyond the first prominent hills described above, the road continues to climb and within a short distance numerous outcrops of coarse black gabbro are exposed. The rock belongs to the formation known as the Duluth gabbro—which includes thousands of cubic miles of rock and is traceable to a point nearly 150 miles northeast along Highway No. 1. (See pages 65-66 for further description and origin of this rock mass.)

Within about two miles the crest of the hill is reached and the traveler is treated to a view that is surpassed at few places. The cities of Duluth and Superior (Wisconsin) occupy the foreground and Lake Superior and its south shore in Wisconsin, the background.

DULUTH

(Population: Federal Census Bureau estimate July 1, 1924, 108,395; elevation: level of Lake Superior 602 feet; high points of bluff: 1400 feet)

Duluth is the third largest city in Minnesota and is a lake port of great importance. The city was named in honor of Daniel Greysolon Du Luth, a French explorer who made a canoe journey to Lake Superior in 1678. He spent two years exploring the region and held a great convocation of Indian tribes on the site of the city September 16, 1679. The first settlement in the region was an American Fur Company trading post built at Fond du Lac in 1817. The first house on Minnesota Point was built by George B. Stunz in 1852.

The harbor is known as the Duluth-Superior Harbor and government statistics are compiled for the harbor as a whole, and are not divided between the two cities. The freight handled in the harbor in 1923 was valued at over $449,000,000. Goods manufactured and handled at Duluth aside from the lake freight had an aggregate value of over $100,000,000. The shipping of iron ore, grain, lumber, coal, and salt constitutes an important part of the trade. Fish-packing and the manufacture of pig iron, steel, cement are of special importance. An economical feature of the lake transportation is that boats coming up from lower lake ports carry coal, salt, and other products and then return with loads of iron ore and grain.

LAKE SUPERIOR

Lake Superior is the largest of the five Great Lakes of North America and the largest body of fresh water in the world. It is of vast importance as a waterway and source of fresh water fish, but its appeal to most people is in its scenery and the invigorating climate it affords near-by land areas.

The name was first used by Father Marquette on a map made in 1673 and refers to its position as the upper lake of the group. The boundary between the United States and Canada passes through the lake and its shores are touched by three states: Minnesota, Wisconsin, and

Michigan. It is 360 miles long and has a maximum width of 160 miles, its area being approximately 32,000 square miles. Its surface is 602 feet above sea level and its greatest depth is 978 feet, or nearly 376 feet below sea level. Isle Royale is the largest island, having a length of 45 miles. The island lies near the Minnesota and Canadian shore, but is a part of Michigan.

The water of the lake is remarkably clear and pure. Analyses show very little organic matter and a maximum of about 60 parts per million of dissolved salts. Cities on the lake have a source of pure soft water without treatment. The lake is remarkable for the low temperature which the water maintains even in warm weather. Some measurements indicate a maximum temperature of not over 48 degrees for the summer months. Only rarely does it warm up enough near shore in bays for pleasant bathing. Large amounts of ice form along the shore during the winter, but the lake is never entirely frozen over. It is reported to have frozen from Isle Royale to Keweenaw Point. The presence of large numbers of moose on Isle Royale is taken as an indication that it has been connected to the north shore by ice, allowing the migration of these animals to the island where they have been marooned ever since. It was estimated in 1924 that there were 1800 moose on the island.

GEOLOGY IN AND NEAR DULUTH

From the point where the city and lake are first seen the paved highway wends its way down a steep grade toward Duluth. At a point a short distance down, the city and civic bodies have provided a place known as "Rest Point," where there is ample space for the traveler to park and enjoy the view. The point is 488 feet above the lake. A brass plate set in a stone monument bears an inscription giving a sketch of the history of the region and drawing attention to salient points which may be seen.

The St. Louis River forms one of the prominent features of the view, winding its way as a broad irregular sheet of water to the westmost tip of Lake Superior. (See Map 7.) The Duluth-Superior Harbor docks are mainly located along the lower stretches of this river and the very tip of the lake, which is protected by Minnesota Point, a long sand bar with a natural opening between it and Wisconsin Point. This sand bar has been built up from the sand dropped by shore currents which swept across the end of the lake from one shore to the other, depending on the prevailing wind.

One of the significant physiographic features which may be seen is that the present Lake Superior does not fill the basin in which it lies. To the southeast a great extension of the basin is outlined by the hills and it requires only a little imagination to visualize the lake at the higher stages known as Lake Nemadji and Lake Duluth, when it completely covered the area of this basin. (See Figure 3.) Another evidence of the existence of the higher lake stages may be seen in the terrace that was once a gravel beach and now is utilized as a road bed for the "Boulevard Drive," about 450 feet above the present lake level. This drive branches off Highway No. 1 a few blocks below "Rest Point," and affords the traveler a series of excellent views of the cities and harbor.

The boulevard is built near the top of a bluff which extends the entire length of Duluth and passes outcrops of gabbro at many places. A convenient place to examine some of the features of the gabbro is on the bluff at "Rest Point." More or less of this material has been excavated for the road. Where affected by the weather the gabbro shows a slight banding of dark and light layers, which dip east about 20 degrees. Weathering along joint planes in the rock has produced spheroidal masses like boulders. A small aplite dike may also be seen to cut the gabbro.

From "Rest Point," Highway No. 1 trends eastward down the bluff for some distance, thence turning back southeast until it reaches the level area along the St. Louis River, where it turns into the streets and the business section of the city.

Many points interesting, both industrially and geologically, may be found at the extreme western end of Duluth, including the village of Fond du Lac. To reach this region Grand Avenue may be followed westward from the corner where Highway No. 1 meets that street.

The first points of interest are the steel plant and cement mill. All of the intricate processes of making steel products from iron ore may be observed.

Those interested in geological detail may continue west to Fond du Lac. Up the river there are two power plants; the upper one has been mentioned in the description of Jay Cooke State Park. Half a mile west of the lower plant, a creek enters the river from the north and along its banks are exposures of sandstone and conglomerate that seem to be Keweenawan sediments. A comparison with the rocks exposed in Section 20, four miles to the north, suggests that the lava flow spreading over 100 miles from the east may have reached its limits in this area.

FOND DU LAC	SECTION 20
Crumpled slate	Vertical slate
White quartz conglomerate	White quartz conglomerate
Red sand and conglomerate with trap pebbles	Trap rock lava flow

The slates are undoubtedly members of the same formation; and the two white conglomerates are probably the same bed. When the lava flow reached Section 20, it apparently did not cover the Fond du Lac area, but produced a hilly country, from which débris was washed down to Fond du Lac, forming a different sort of conglomerate.

After many trap rock lava flows had accumulated around Duluth, the lava evidently had more difficulty in reaching the surface of the ground and a large amount of the material forced open and filled a huge chamber. This great chamber full of magma (lava underground) finally cooled down to form a solid coarse grained rock, the *Duluth gabbro*. A side trip near the steel plant in the west part of Duluth will be of interest to geologists who wish to see the details of the relations of this gabbro to other rocks.

One of the most interesting regions to the geologist may be reached by following a road that passes between the Universal Portland Cement mill and the steel mills, to Short Line Park, a station on the Northern Pacific Railway. Just north of this station a stone crusher is operating on stone from a quarry in basalt flows. If one follows the Duluth, Winnipeg and Pacific Railway east from the stone crusher he sees numerous rock exposures. Four successive lava flows, dipping east at angles of about 10 degrees, may be distinguished along the railway cuts by their softer amygdaloidal upper zones. One of them has a pillow structure (ellipsoids) near the bottom. One is cut through by the tunnel of the railway. East of the tunnel the character of the rocks changes gradually. The diabase texture of the basalt of the flows changes to a sugary texture, and there are dikes and stringers of other rocks in increasing numbers. Finally at the east end of the next larger railway cut, east of the tunnel, the Duluth gabbro begins to appear. From this point to the center of Duluth, gabbro is exposed in about as large quantities as anywhere in the world.

The dikes and stringers in the flows near the gabbro are pegmatites of unusual character.

The first half mile of gabbro exposed along the railway is not the sort of rock exposed in most places, but evidently is the part of the great chamber full of magma which was first to solidify, and collected at the bottom of the chamber.

There are many points of interest throughout the city but only the more important are described in this chapter. The city has reserved space for a park along each little creek which flows down over the 800-foot bluff that borders the lake. The rocks of the region are well exposed in each of these.

At Fairmount Park, in the western part of West Duluth, the outcrops are representative of the main mass of the Duluth gabbro. The other parks along the bluff show special and unusual varieties rather than the normal and abundant rock of the formation.

Lincoln Park, at Twenty-fifth Avenue West, shows near the highway abundant outcrops of a coarse gabbro, rich in feldspar—anorthosite. If one walks up the creek towards the upper end of the park, a change can be noted in the rocks. Underlying the coarse gabbro, and west of it, is a mixture of fine black gabbro and "red rock." These two are evidently related and both intrude the coarse gabbro in dikes. The "red rock" is considered an "aplite" derived from the black gabbro.

A side trip near Lincoln Park might be made by geologists who are interested in the development of gabbro varieties.

The Hermantown Road starts northwest from Piedmont Avenue and two miles out beyond the boulevard, reaches the east side of Section 25, where it turns west. There are some outcrops north of the road about one hundred yards west of this corner, that were once prospected for iron. The gabbro is banded and some bands have unusually large amounts of titaniferous magnetite. Exposures are perhaps even better at the barn south of the road a little farther west.

At the road a mile farther west is an outcrop of anorthosite, much like those included in diabase along Highway No. 1 farther east, near Split Rock River, Beaver Bay, Tofte, and other places.

At Thirteenth Avenue West and Third Street, is a small quarry in "red rock." East of the quarry is coarse feldspathic gabbro, anorthosite, which has evidently been intruded by red rock. The contact is brecciated and the rocks so changed that there seems to be an almost complete gradation between two very different rocks.

Near Cascade Park, where Mesaba Avenue crosses Lake Street, just up the hill from the center of town, the character of the rocks changes abruptly. The great gabbro mass that extends from the steel mill at Gary to the center of the city, is again replaced by a series of surface volcanic rocks. Within a block above the park there is an outcrop of dense black rock which shows on its weathered surface that it was formed by a volcanic explosion. It now consists of fragments of various sizes well cemented in a fine ash or dust from the volcano.

The actual top of the gabbro mass, where lava flows were intruded by the later underground magma, is not exposed near Highway No. 1. If one wishes to see such a contact it can be best seen by a side trip from Cascade Park or Mesaba Avenue, out County Highway No. 11. At a point one and one-fourth miles from Cascade Park the outcrops are visible in a hill one-fourth mile northeast of the rock. Here black basalt is underlaid by gray gabbro.

From the center of the city, eastward for many miles, the main rocks exposed are volcanic lava flows. The most convenient place for one to see such a sequence of flows is reached by turning two blocks to the left of Highway No. 1 (Superior Street), about Second or Third Avenue East. Then if one goes east on Second Avenue to a point between Fourth and Sixth avenues, rocks are found in the bluff near the road. (See Figure 9.)

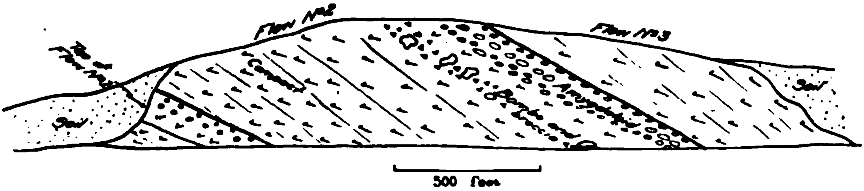


FIGURE 9. CROSS SECTION OF OUTCROP SHOWING THREE LAVA FLOWS. SECOND STREET BETWEEN FOURTH AND FIFTH AVENUES EAST, DULUTH. AFTER GROUT

A longer series of flows can be counted by anyone who cares to walk along the shore of the lake from Fourth to Fourteenth Avenue East. About ten flows may be distinguished by their soft amygdaloidal zones, alternating with hard, black, dense basalt. At Twelfth and Thirteenth Avenues East the flows are interrupted by some sandstones, which no doubt derived their material largely from the flows. The sands are conspicuously cross bedded and end abruptly at a fault plane near Thirteenth Avenue.

Chester Park is along a creek in the lava flows. East of this series of flows the lake shore cuts into a large sill of diabase from Fifteenth Avenue to Twenty-fifth Avenue East. The rock is much like the gabbro of the western part of the city and may be connected with the same chamber. The top of this sill shows a change in the color of the rock from black to red. The change is easily examined in Congdon Park, Thirty-third Avenue East, by walking up the creek from Superior Street which is here about four blocks above the lake. The sill was formed by the forcing of a sheetlike mass of magma between the lava flows. Having solidified under cover, the rock is coarsely crystalline as compared with the flows and the change in composition from black to red is a result of segregation within the mass before solidification. Presumably the red portion rose to the top, somewhat like cream on milk, because of its lighter weight.

Above the sill is a series of lava flows and fragmental volcanic rocks, that are bright red, noticeably different from the black basalts farther west. These extend to about Forty-fourth Avenue East; and thence, alternating with darker flows, to Lester Park beyond Sixtieth Avenue East.

Lester Park is along the banks of Lester River which cuts a very beautiful gorge in basalt lava flows. East of Lester Park for about a mile, Highway No. 1 crosses another big sill like that from Fifteenth to Twenty-fifth avenues. It grades into a reddish rock at the top and has more flows east of it. The surfaces of many of the outcrops are polished and striated by the glacier. There is a more or less continuous exposure along shore of a series of flows with well-developed amygdaloidal tops to the city limits which are just north of Clifton, a station on the Duluth and Iron Range Railway.

CHAPTER VII

HIGHWAY NO. 1 ALONG THE NORTH SHORE OF LAKE SUPERIOR

The north shore of Lake Superior is a wonderfully beautiful country with its broad expanses of clear blue water backed by a coast which is almost mountainous over much of its length. To make the region more readily accessible the Minnesota Highway Department has completed a highway which follows the lake shore from Duluth to the Reservation River, thence turning inland about ten miles to the Canadian border. In this chapter some of the features of the lake shore country are described but the space is inadequate for many things worthy of note. Route maps Nos. 7 to 13 show this area in detail. Northeast of Two Harbors the country is thinly settled and the camper will find numerous excellent places to stop.

The city limits of Duluth are less than a mile southeast of Clifton station on the Duluth and Iron Range Railroad. The shore opposite Clifton is rocky and forms a rounded point where the Talmadge River flows into the lake, through a small gorge in Keweenawan basalt or trap flows. (See Chapter II.) Amygdaloidal or vesicular tops of flows are not closely spaced along this stretch of rock exposures, indicating rather thick flows with a trend or strike nearly parallel to the shore line. A state fish hatchery is located on the east bank of French River just north of the highway bridge. A short distance beyond the French River the rocks are concealed and the first outcrops a mile beyond form a point made up of a thick basalt flow with thick amygdaloidal beds exposed on each side of the point. Scattered outcrops occur from here to Sucker River where a broad bay has a gravel beach. A prominent point at the northeast side of the bay shows the first outcrops of a hard, coarse, black diabase or gabbro sill like that at Lester Park. The rock is beautifully mottled where it is exposed to the action of the weather or the grinding and polishing effect of the waves. The rock shows a well-defined banded structure, dipping toward the lake, at an angle of about 15 degrees with a trend or strike of north 55 degrees east. Glacial striae are common on the smooth upper surfaces of the rocks. These show that the ice moved in a direction about 60 degrees west of south. The diabase forms a very rocky and bold coast and the hills back of the point stand out on the comparatively level terrace or beach which extends from Lester Park to Arthur. The diabase is continuous along shore to the mouth of Knife River in Lake County, a distance of four miles.

The character of the tree life along the shore from Duluth east deserves comment. Nearly all of this area has been burned over s cently that only brush has grown up. At places, however, the older have escaped and these consist mainly of pine, balsam, and spruce some birch and poplar. The typical hardwood trees occurring so dantly in the southern counties of the state are almost entirely lacking

LAKE COUNTY

(Total area 2100 square miles; covered by water 262 square miles)

Lake County covers a large area 36 miles wide extending fro coast of Lake Superior north to the Canadian boundary, a maximum tance of nearly 90 miles. Much of the county is rough and rocky is unsettled. The Superior National Forest covers a large area i northern part and the remainder is patrolled by the State Forest Se There are many lakes in the northern half of the county and they excellent fishing. Many fine trout streams empty into Lake Superio

Knife River
Population 125

Knife River is the largest village between Duluth and Two Ha Previous to 1923 it was the head of the Duluth and Northern Minn Railroad which was built principally for logging o tions. The traffic was not sufficient to support it the timber operations ceased and in 1923 it was tor

The diabase sill described in the preceding pag not exposed east of the mouth of the Knife River. On the east ba that stream and northward along the road are numerous outcrops of with well-developed amygdaloidal tops. Outcrops of this type co to a point about a mile east of Larsmont station beyond which ther no exposures along the road as far as Two Harbors.

Two Harbors
Population 4546

Two Harbors received its name from the two small bays or n harbors of the coast. The westernmost bay which is utilized fo harbor is known as Agate Bay from the agates in the sand along the shore. The eastern bay is k as Burlington Bay. The city is the location of the and iron ore docks of the Duluth and Iron Range road which brings down large amounts of ore from the Mesabi and milion ranges to be shipped to eastern lake ports. A new hotel was in 1924 and a tourist camp on Burlington Bay affords a fine spot camp on the lake.

Geology at Two Harbors.—On the shore of Burlington Bay just the tourist camp is a great series of lava flows with amygdaloidal From the sandy beach of the bay to the power house, the shore t diagonally across the strike of the rocks and five distinct flows are posed, forming sharp points of rock projecting into the bay. The d between Burlington and Agate bays is formed by the fifth. One of

amygdaloidal beds directly below the tourist camp is unusually thick and shows much pink laumontite and white calcite. The main flow contains agates which were formed by filling holes once bubbles or gas holes in the flow by silica deposited concentrically forming the agate structure. The main harbor in Agate Bay is protected by a breakwater. The inner part of the bay shows no outcrops but on the southeast side beyond the ore docks are prominent cliffs. Here are found three flows with amygdaloidal tops which weather out easily. The trend or strike of the rocks is apparently north 45 degrees east.

Northeast of Two Harbors the road follows a level terrace with a red, lake clay soil deposited by Glacial Lake Duluth. (See Figure 4.) No exposures of rock occur along the road as far as the bridge over the Stewart River where the flows are again exposed. Along the lake shore, however, outcrops are frequent and about a half mile west of the river a considerable amount of red sand is incorporated in the amygdaloidal portion of a flow.

Just beyond the Stewart River the old inland highway turns northward and follows a route ranging from two to ten miles from shore to Cross River in Cook County where it returns to the shore.

About two miles beyond the Stewart River is a prominent bluff on the lake shore and Highway No. 1 has been blasted out along the face of this cliff with much difficulty. The rock that forms the cliff is a diabase or gabbro which was intruded into the flows of the region. It is the same type of rock as that found at Lester Park. The flows may be seen exposed along the water's edge beneath the diabase, and at the northeast end the contact is exposed at the level of the road. The road rises to a height of 125 feet above the water and the bluff is 120 feet higher. The cliff originally formed one of the boldest places along the Minnesota shore. Widely spaced joints cut the rock forming huge blocks, which gave much trouble by sliding down when the road was being constructed. Weathering along the joint planes has rotted the rock at places and a few are filled with secondary minerals, some of which are rare. The bluff trends northward away from the road and forms a high inland ridge. Abundant outcrops of basalt and amygdaloidal basalt flows are found along the road for a half mile beyond the cliff; to the northeast the red, lake clay covers the rocks as far as the Encampment River.

Along shore at the mouth of the Encampment River a group of Minneapolis families have organized a summer colony under the name of "Encampment Forest Association." Many fine white pines line the road, forming the best stand of these trees along the coast. Encampment Island lies somewhat to the east of the mouth of the river. Opposite the island on the mainland is another ridge not unlike the one described just above, but the rock is porphyritic, that is, it has large crystals of feldsp bedded in a matrix of finer grained material. The decomposed covering much of this rock is to be especially noted. It is a rusty crumbly material which was formed from the hard black diab weathering, that is, by the action of water and air. This is an e of the manner in which soil and loose material has been formed weathering of the various types of rocks.

On the north side of the point and along the shore the contact diabase intrusive with the flows may be seen. The flows overlie the and are locally tilted up at an angle of 45 degrees. Farther northea shore the flows may be seen to have a dip of 10 degrees toward t The flows are much seamed and fine specimens of the minerals lau epidote, and chlorite may be had. The beach gravel of the bay the point contains many agates which may be most easily fou at the water's edge.

The road passes over a creek and beyond this is another poin high cliff along the water's edge for some distance. Beyond t the coast is relatively low and a level beach extends inland for s tance, and along the coast past Castle Danger. This rather extens area is doubtless an indication that there are no diabase intrusions the rocks as they are resistant and tend to form hills and ridges.

Geology at the Gooseberry River.—The Gooseberry River emp Lake Superior about two miles beyond the settlement of Castle The name of the river is a translation of the Ojibway name. Ju the bridge is a falls with a drop of 25 feet, and less than 300 fe stream are two falls with a total drop of fully 75 feet. (See Plat Upstream about a mile from the bridge is still another. This falls show very clearly the effect of the variation in hardness on the erosion by running water. Examination of any of the fal that the water plunges over a massive basalt flow which is und the soft amygdaloidal bed of the flow beneath. This softer m undercut or worn out more rapidly than the hard bed above, thus the massive bed to break off in large blocks leaving vertical faces

Below the lowest falls on the east side is a high basalt cliff, west side is largely clay and the river has cut a wide channel in material and now follows a pronounced meander in the valley. shore, west of the river as far as the Lind farm, is a very in stretch of coast. The beach gravel near the mouth of the river many agates broken out of the amygdaloidal rocks which form th Just east of the Lind farm a thick amygdaloidal bed (20 to 25 f beneath a massive basalt. The amygdaloidal bed is heavily mi and shows many fine specimens of calcite, including some ver parent material, laumontite, quartz, and minor amounts of other Geodes, or small openings lined with crystals, are common.

Beyond the river the road mounts a high hill and the road cuts expose the flows for some distance. From the crest of the hill a wonderful view may be had of the coast to the southwest as far as Two Harbors. The road passes over the crest into a small valley and then swings southward around another hill and from this point an equally fine view is afforded of the coast to the northeast, where its rugged, mountainous character is very striking.

Beyond the hill the road continues down a long grade and passes close to shore. Ahead, two prominent knobs stand out conspicuously near the shore, and beyond a lighthouse may be seen. To the left of the road are good examples of the abandoned shore lines or beaches. The road follows the lower level, and two lines of cliffs, one back of the other, mark successively higher ones.

The rocks along this part of the road are decidedly red and contrast strikingly with the black basalts and diabases which are found from Duluth to this point. This rock is probably a lava flow as it is very dense like most rocks which cool quickly. The red, dense rocks are known as rhyolites or felsites. (See Glossary.)

The Split Rock River flows through a broad valley in the basic flows which replace the red rocks found to the southwest. At its mouth it empties through a narrow gorge in rock, whence its name. About three fourths of a mile northeast of the river and west of the lighthouse are two prominent white hills which are composed of anorthosite. A mass of this rock has been blasted away along the road, exposing it for easy examination. It is made up almost entirely of one mineral, plagioclase feldspar, forming a white or nearly colorless rock with a greenish tinge. It is an unusual rock and will doubtless be utilized some day as a decorative stone, although it is harder than most rock used for that purpose. The origin of this rock has been the source of much speculation by geologists. It forms several pronounced knobs north of the road in the region of Lighthouse Point. The prevailing rock, aside from the anorthosite, is a coarse, black diabase much like that noted at several places along shore. Just beyond the lighthouse amygdaloidal basalts are found outcropping along the road. A short distance farther on a small gorge cuts deeply into the solid rock, and on the south side a coarse, red rock of the syenite or granite type is exposed. From this point to Beaver Bay, a distance of several miles, the road passes over a rough rocky country. Here outcrops of the coarse diabase are practically continuous. The coast is rocky and bold, due to the erosion of the diabase along the well-developed systems of joints.

Beaver Bay.—At Beaver Bay the Beaver River empties into the lake through a gorge in diabase. The abundant exposures of diabase in this region lead to the adoption of the name Beaver Bay diabase for the series of diabase intrusives found along the coast in Minnesota. From the bridge a view of the lower falls may be had. The village of Beaver Bay was the county seat of Lake County until 1888, when the offices were moved to Two Harbors. A post office, store, and garage mark the location at present. A summer colony of Minneapolis people controls the land on the west side of the bay.

Just southwest of the mouth of the river are outcrops of anorthosite in diabase; beyond this, and forming a part of the southwest headland. are cliffs of red porphyry. On the southwest side of the headland is coarse diabase with huge blocks of anorthosite included in it. Beyond this is an exceedingly coarse phase of the diabase with a mottling on the weathered surface due to the alteration of the more soluble minerals, especially olivine.

Just back of the post office are other anorthosite masses in diabase. and anorthosite may be observed in the road cuts just east of the post office. The northeast headland of the bay is apparently all diabase.

Northeast of Beaver Bay, Highway No. 1 passes close to shore over the same type of diabase found east of the bay. Several rocky islands dot the shore, and ahead the Great Palisades stand up, above the surrounding country. About a mile northeast of the headland several anorthosite masses are found along shore and on the islands. North of the road is a wave-cut cliff which swings toward the present shore three miles northeast of Beaver Bay, where the road passes around the old cliff. Many exposures of diabase and flows are found along the road and a gradation of dark diabase to red syenite may be noted.

The Great Palisades.—The Great Palisades form one of the prominent points along shore and some time may be profitably spent by the more adventuresome traveler climbing over the rock mass. At the west side a path leads from the road to the summit of the hill where one may obtain a remarkable view of the coast in both directions. The Sawtooth Mountains of Cook County stand out to the northeast. Inland the topography is very rough and several rounded white knobs of anorthosite are conspicuous. To the southwest the coast may be seen as far as the lighthouse at Split Rock. The five islands off the coast near Beaver Bay and the many points and inlets form a most picturesque coast line.

The palisade hill is composed of a dense, red rock which on close examination is found to be porphyritic; that is, it has visible grains of smoky quartz and white and red feldspar with a dense ground mass. It may be called a rhyolite porphyry. The maximum height of the hill is 315 feet and the vertical cliff on the lake rises over 200 feet at places. At the base of the cliff along the southwest side the porphyry overlies basalt flows with much amygdaloidal material. The dip is toward the lake, so that at the place where the cliff faces the open lake, the porphyry reaches the water level. Near the contact the porphyry is beautifully brecciated and banded, probably due to the flowing of the porphyry over the basalt flow. The cause of the vertical cliff of the palisades is found in this contact. The amygdaloidal portion of the underlying basalt flow is easily eroded by the waves, thus leaving the rock above unsupported, causing it to break off along the vertical joints or fractures. The condition is essentially the same as that forming water falls in rivers. Beyond the palisades is a broad terrace which extends to the Baptism River.

The Baptism River.—The Baptism River flows through an exceedingly rough country which may be seen to advantage from the steel bridge over the gorge. (See Plate IV B.) At its mouth are cliffs of rhyolite flows similar to the rock at the Great Palisades. The rhyolite is not extensive, as basalt flows are found a short distance southwest. Just east of the mouth are a series of cliffs which form the Little Palisades. (See Plate V A.) The river flows in a deep, but comparatively narrow, gorge near its mouth. Basalt and rhyolite flows outcrop along the gorge. Some diabase intrusions cut the flows. At the first falls a half mile upstream the river plunges over a massive, dense basalt with the channel along joints. The gorge above the first falls is narrow and about a quarter of a mile farther up is a series of small falls due to erosion along amygdaloidal beds. About one and one-half miles above the road is a large fall where the river plunges over a vertical cliff fully 50 feet high. (See Plate IV C.) The rock at the falls is a rhyolite porphyry similar to that at the Great Palisades. This massive red rock is undercut along the soft basic flow on which it rests. This stream and its many tributaries furnish perhaps the best trout fishing along the north shore. The traveler has probably noted the brown color of the water in most of the streams in this region and wondered at its cause. It is a result of the organic matter which is taken up by the rivers from the forests and swamps. This material is not in the least harmful.

Beyond the Baptism River the road follows a route some distance from the shore to avoid the extremely rough coast along the Little Palisades. The first road cut exposes the rhyolite porphyry continuous with that which forms the palisade cliffs. The road swings farther inland to pass around a gorge. West of the bridge an old aerial tramway standard is located on the south side of the road. The tramway led to an old quarry in anorthosite a half mile north of the road. This is known as the Crystal Bay quarry.

Northeast of the creek the road swings shoreward around a basalt bluff which marks the old shore line. The terrace is broad from this point on for a mile or more. Basalt and diabase outcrops are numerous along the road. At a point three miles northeast of the Baptism River the road swings around a big hill which consists principally of anorthosite,

PLATE IV

A. Double falls of the Gooseberry River, 300 feet below Highway No. 1. Each fall is formed by the undercutting of a massive basalt flow along the amygdaloidal top of the flow beneath.

B. Valley of the Baptism River. The pronounced hills in the distance are composed of intrustive diabase. This topography is typical of the Minnesota coast of Lake Superior.

C. Falls of the Baptism River, 1½ miles above Highway No. 1. The 50-foot cliff over which the river plunges is composed of hard rhyolite, which is undercut along a softer flow beneath.

PLATE IV

A

B

C

but with diabase along the lower part at places. Some of the rock has been blasted down for the road thus exposing the fresh material. The anorthosite is much darker than that found at Beaver Bay and Split Rock. Beyond this the road follows a broad terrace and the coast is less rugged than that near the Baptism River. Three beach or terrace levels may be noted from this point to Little Marais; one is a short distance above the present lake level, a second is just below the road, and the third or upper terrace is occupied by the road.

From Little Marais to the Manitou River the road follows the same level beach or terrace, and gravel deposits form a mantle over the solid rock. The coast line is regular and the country much less rugged than that to the southwest. An exceptionally well stratified sand and gravel deposit is located just at the west approach to the bridge where road material has been removed. This deposit may represent an old delta formed by the river pouring into the lake when it stood at a much higher level.

The Manitou River retains its Ojibway name which means spirit. The river has a remarkably deep and narrow gorge where the new steel bridge spans it. The cause of this gorge may be seen in the beautiful falls a short distance upstream from the bridge. The falls are not visible from the road, as there is a sharp bend in the river, but they may be reached in a few minutes by following a path along the east bank. The river makes a right angle turn and plunges over a massive basalt bed with a total fal of nearly one hundred feet. (See frontispiece.) At the base is a amygdaloidal bed several feet thick, which the stream is undercutting, thu maintaining the falls, which gradually migrate upstream leaving the na row canyon seen between the falls and the bridge. Between the bridg and the lake, a distance of only half a mile, three more falls with a seri of rapids give a total drop of several hundred feet. The last fall plung the water directly into a small cove of Lake Superior and may be se by passing boats. The Manitou, especially in its upper stretches, affor good trout fishing.

About half a mile northeast of the Manitou River the road descen to a lower terrace which continues at almost the same level for seve miles. The gravel of the abandoned beach covers the rocks except for few outcrops of basalt. The Caribou River emerges by a fall from t hilly inland country onto the terrace which the road follows.

COOK COUNTY

(Total area, 1680.4 square miles; covered by water 213.56 square miles)

Cook County was named in honor of Major Michael Cook, of Fa bault, who was mortally wounded in the battle of Nashville, December 1864. The county forms the extreme northeastern part of the state a

A. THE LITTLE PALISADES. COAST OF LAKE SUPERIOR EAST OF THE MOUTH OF THE BAPTISM RIVER

B. GROUP OF WHITE PINE (PINUS STROBUS), SUPERIOR NATIONAL FOREST

C. FOREST OF SPRUCE AND BALSAM, STEWART RIVER, HIGHWAY NO. I, NEAR TWO HARBORS has a roughly triangular shape, being bounded on the west by Lake County, on the north by Canada, and on the southeast by Lake Superior. Its extreme length east and west is 72 miles and its width 54 miles. The county is mostly unsettled and is traversed by but few roads, the only ones of great length being Highway No. 1 along shore, and the Gunflint Trail extending from Grand Marais north and somewhat westward to Gunflint Lake. Lakes and streams are numerous and the area is one of rare beauty and charm, and is especially adapted to canoe trips, but also furnishes ideal conditions for campers traveling by auto.

Highway No. 1 enters Cook County a short distance east of the Caribou River, where it continues on the terrace that extends from the Manitou River northeastward. The area near the shore has little relief. The three beaches or terraces are more marked here than at any other place along the coast. The road follows the intermediate beach. This section of the coast has been burnt over recently and has few trees of any size. At Two Island River the absence of a gorge is noteworthy. This is a result of the low and comparatively level land along the coast. The river receives its name from the two rocky islands near its mouth.

The lack of conspicuous hills along the coast east of Little Marais may be accounted for by the absence of the diabase intrusions such as those which stand up as prominent hills in the Beaver Bay region. No outcrops of rocks other than lava flows occur along the road northeast from Little Marais to Tofte. The road follows the shore closely to Cross River or Schroeder. The bridge over Cross River is just below a fall and cascade. Several potholes are exposed in the massive basalt flow which forms the falls. The river was given its name in 1864 by Thomas Clark, assistant state geologist, because of a cross which had been placed at its mouth in 1843 by Father Baraga, a Catholic missionary to the Indians.

Temperance River empties into Lake Superior only a little more than a mile east of the mouth of Cross River. It is one of the longer rivers of the north shore, as it starts near the west end of Brulé Lake in north central Cook County. The highway crosses the stream a short distance above its mouth, over a very narrow gorge. At the bridge are many examples of potholes which have grown together, forming the gorge. The rock consists of the usual basalt flows dipping toward the lake at an angle of about 12 degrees. The river was named by Clark in 1864. The name originated from the fact that the mouth of the river, unlike most of the other streams entering the lake, was not blocked by a bar!

Beyond the Temperance River the road continues to follow a prominent terrace or abandoned beach and the country is comparatively level, although to the east Carlton Peak looms up close to the lake.

Carlton Peak.—The name is applied to a conspicuous peak located a mile and one half inland from the lake directly behind the village of Tofte.

It is composed of huge masses of anorthosite overlying, or embedded in diabase. The anorthosite is rounded off in the form peculiar to it and the peak is thus relatively flat on top. It rises 927 feet above the lake and forms one of the most conspicuous landmarks along shore, especially as it rises out of a comparatively level stretch of coast. It may be climbed with little difficulty and affords an excellent view. The foot of the peak may be reached by an auto road which extends north from the church at the east end of Tofte.

Tofte
Population 100

Tofte was named for a family of early settlers in the region whose name was derived from their former home in Norway. A store, garage, hotel, and a few houses comprise the village. A tourist park is maintained on the lake shore. A considerable area of cleared land around the village exposes the outlines of the main terrace on which the village is located. Just back of the group of farm buildings is an old shore line, and others may be noted up the slopes of Carlton Peak.

Northeast of Tofte the country is comparatively level near shore, to Onion River. Here the road enters a region, which has not been burned over recently, covered with a thick growth of birch, spruce, balsam, and other trees. The attractiveness of the country is greatly increased by this primeval covering of trees.

Lutsen is the name of a settlement centering around a resort at the mouth of the Poplar River. Between the resort and Highway No. 1, which is a short distance inland, the river flows through a gorge with many cascades and falls. Many potholes of various sizes are found near the stream level. A large one receives the water from one fall and at places others have joined to form the gorge. Footpaths follow along the gorge and make it easy of access.

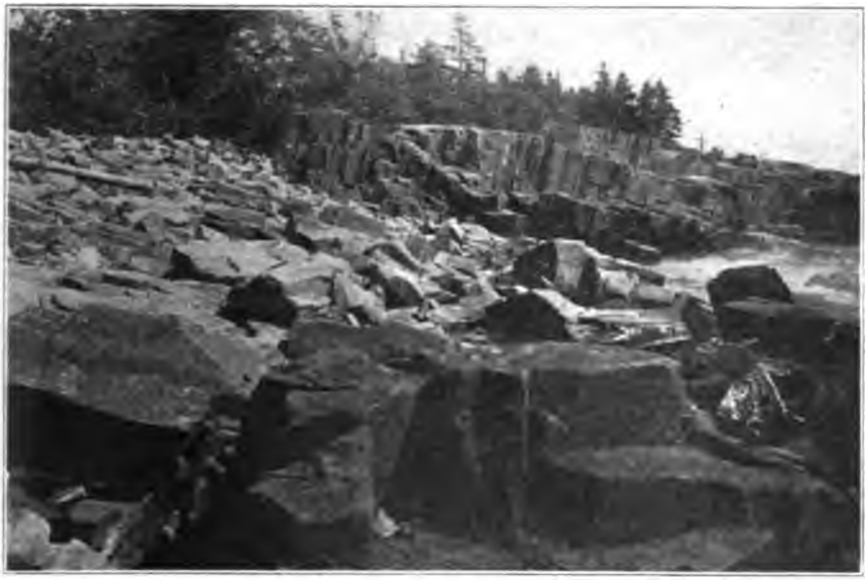
From the Poplar River northeastward the road follows the main terrace and is close to the lake. The road is level and there are but few exposures of rock. The shore is a continuous outcrop of reddish basalt with many amygdaloidal beds showing excellent zeolite fillings. In the region of the Cascade River the exposures are of black massive diabase at places coarse enough to suggest an intrusive. The Cascade River is named from a series of beautiful falls found a short distance above the road, which crosses but a hundred feet above the mouth of the river.

About two miles northeast of Cascade River the road turns inland and gradually mounts to one of the higher terraces and follows this east nearly to Grand Marais. About a mile from the coast a road branches to the east, and runs south to Good Harbor Bay and Thompsonite Beach. (See Map No. 11.) This is the source of the thompsonites which are much used in Minnesota as semiprecious stones. Thompsonite is one of a group of minerals known as zeolites. Commonly these minerals assume a radiating form and this with the hardness and desirable colors gives the thompsonites their value. The stones are found embedded in a massive diabase especially in the amygdaloidal portion near the top but are most easily gathered from the beach gravel where the diabase is broken up. Red sandstone and shale are also exposed in the bay in greater amounts than elsewhere along the Minnesota coast.

Grand Marais
Population 443

Grand Marais is the county seat and largest village in Cook County, and also is the largest settlement in northeastern Minnesota east of Two Harbors. The name, French for Great Marsh, was applied because of a marsh or swamp situated at the head of the bay and harbor. The harbor is the first one east of Two Harbors that is well protected. Tourist camp sites, hotels, garages, and stores provide everything the tourist may need. This is also the point where the Gunflint Trail leaves the coast on its way to Gunflint Lake on the northwest border of Cook County. (See page 88.) An excellent view of the town and harbor may be had from the hill which the trail ascends a mile out of town. The harbor at Grand Marais owes its existence to a hard columnar diabase which resisted the erosive power of the waves while the softer rock behind it was worn down. This is a fine example of the columnar structure found in certain igneous rocks. (See Plate VI A.) The structure is believed to be due to shrinkage on cooling, resulting in fractures which tend to form six-sided blocks or prisms. The best known example of this structure is the Giant's Causeway on the coast of Ireland.

From Grand Marais northeast, the road follows the upper of two abandoned beach levels and a line of bluffs to the north marks a still higher shore line. The rock along the road is a conspicuously red and dense rhyolite at places. Other types of rocks are interbedded with the rhyolite as may be seen along shore at many places. About two and a half miles east of Grand Marais is a rocky point of diabase and in the bay beyond is a dike of intrusive diabase with small anorthosite fragments. In this region the dip of the rocks varies and is locally steep indicating considerable disturbance by this intrusive. A short distance east of the point is a spherulitic rhyolite overlain by a sandstone. This interesting series of rocks may be found along shore where the old Highway No. 1 drops down to the lower beach near a group of houses. The Devil Track River flows into the lake about four miles east of Grand Marais. It is normally a small stream deeply entrenched in rhyolite flows, but in times of flood it becomes a torrent as is shown by the ruins of the large concrete bridge, wrecked in 1922. For nearly a mile beyond the river an unusually fine wave-cut cliff may be seen north of the road. This represents the last level which the lake maintained for any length of time before it dropped to its present stage. A mile northeast of Devil



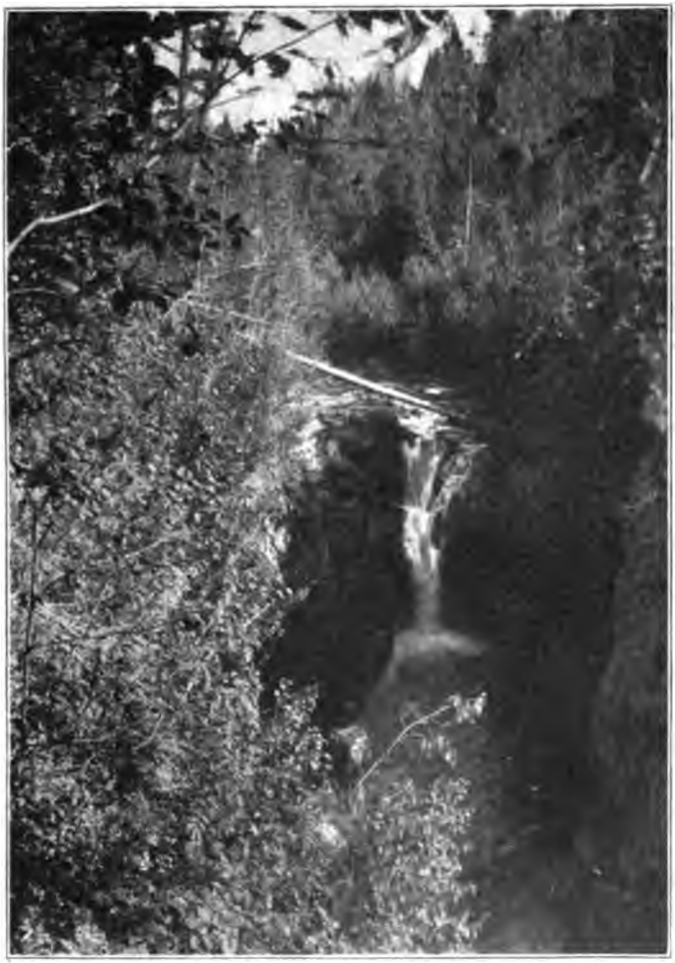
A. COLUMNAR JOINTING IN DIABASE. HARBOR AT GRAND MARAIS

B. ABANDONED SHORE LINE OF LAKE SUPERIOR, COOK COUNTY

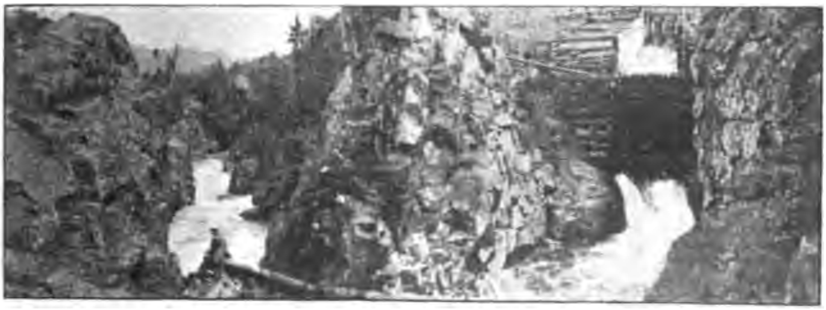
Track River the red rocks give way to the usual basalt flows with amygdaloidal tops. These are well exposed at Cow Tongue Point. In the bay and along Kimball Creek rhyolites occur again. The rhyolites are easily broken and this probably accounts for the bay. The rhyolites continue for some distance to the east and beyond the rhyolites basalt flows extend to the Brulé River.

The Brulé River.—This is one of the largest streams along the Minnesota coast. The south branch has its source at the east end of Brulé Lake which, as has been previously noted, also feeds the Temperance River at its west end. This feature of two outlets is probably due to the rock basin in which the lake is located. Brulé is the French word meaning burnt, and was probably applied because of partly burned areas along the stream. The river flows in a comparatively shallow gorge where the road crosses it near the mouth; but a short distance above the bridge, high banks rise on either side and it is entrenched in a gorge hundreds of feet deep at places. For picturesque wildness the stream is not easily surpassed. A well-marked trail leads upstream from the bridge on the west side and furnishes an easy path up to the series of falls from one to one and one-half miles above the road. At the bridge are basalt flows, but upstream the gorge is entrenched mainly in rhyolites. Several cascades and one fall of about 20 feet are located along the gorge below the main fall, which is often termed the Pot Hole Falls. (See Plate VII.) This fall presents a most remarkable phenomenon. The total height is perhaps 70 feet and just above the brink the river is divided into two parts by a jutting rock mass. The eastern part, which is somewhat the smaller, plunges over the vertical cliff into the pool below, the larger part plunges into a huge pothole in the western channel just before reaching the crest of the bluff and the water disappears. Although the point where it issues cannot be seen, it must empty in the very deep pool below the falls as the river shows no diminution.

Northeast of the Brulé River the road turns inland for several miles but nears the shore again at Hovland. No outcrops are found along this stretch, but the road cuts through red, lake clay. From Hovland northeast outcrops, mostly of diabase, are abundant along the road. A big range of hills may be noted a mile or more inland. Farquar's Peak is the most conspicuous knob. This range is composed of gabbro or diabase of the type found at Duluth and Beaver Bay. Near Big Bay much rhyolite is visible along the road. On the west side of Big Bay rhyolite porphyry may be seen in contact with diabase where a rock ridge crosses the road. The diabase shows up conspicuously at the Reservation or Mesquatawanga River and eastward along the shore and road. This rock has been traced to the west and apparently is a part of the Duluth gabbro. Just beyond the river the road leaves the coast and it does not



A. POT HOLE FALLS, BRULÉ RIVER, 1½ MILES ABOVE HIGHWAY NO. 1, MORE THAN HALF OF THE RIVER FLOWS INTO A MAMMOTH POT-HOLE HIDDEN BY THE FOLIAGE TO THE LEFT



B. HAIRPIN TURN IN SPLIT ROCK CANYON OF THE PIGEON RIVER return to it again in Minnesota but crosses the Pigeon River into Canada several miles from the lake. The road ascends a long grade and is flanked by many bare gabbro hills.

About two and a half miles northeast of Reservation River the road bends around a conspicuous red hill which has exposures of a variety of rocks. Most of the main ridge near the road is basalt porphyry with large plagioclase phenocrysts often aggregated into starlike forms. The term glomeroporphyry has been applied to this type of rock. Cutting the basalt porphyry is a network of dikes. A fine-grained basalt dike cuts into the porphyry near the road on the south side. This dike is cut by red dikes. The smaller dikes which cooled quickly are rhyolite, but they were apparently formed from the same magma and at the same time as some large masses of coarse syenite near by. To the west and north the hills are composed mainly of coarse, red syenite and about 200 yards northwest of the road a gradation from syenite to coarse diabase or gabbro may be seen.

The road continues up grade nearly to Mineral Center where a more level area is settled and partly cleared. To the east are the high, practically mountainous ridges of the Grand Portage and Pigeon Point regions. These high ridges are formed by large sills and dikes of diabase intruded in the Rove slate (see page 14) which occupies an area along the border from Pigeon Point and Grand Portage Bay to Gunflint Lake. The slate is soft and has been eroded away leaving the hard, tough diabase standing high above it.

At Mineral Center a road extends south, and eastward from Highway No. 1 to the picturesque and historic village of Grand Portage which is located on Grand Portage Bay. (See Map No. 12.) This historic place has been mentioned in Chapter II as the first more or less permanent post established by white men within the area of Minnesota. Further details on the Grand Portage trail are given on the following page. The village is still the home of Indians and the surrounding area lies within a reservation which extends from the Reservation River to a line from Hat Point northwestward to the Pigeon River, a mile below the International Bridge. (See Map No. 12.) The bay is flanked by a very rugged country which adds to the scenic effect. Mount Josephine forms the divide between Grand Portage and Waus-wau-goning bays and rises to a height of 703 feet above the level of Lake Superior.

North of Mineral Center, Highway No. 1 follows the valleys and low points among the hills. This region is heavily timbered with spruce, balsam, birch, and pine, so that only occasional glimpses of the hills may be had. About five miles beyond Mineral Center and one and one-half miles from the border, the road crosses the Grand Portage trail. (See Map 12.) Brush has grown up in it now, so that it is only a footpath.

but its history is one of great interest. Highway No. 1 ends at the International Bridge over the Pigeon River. The river gorge at the bridge is mainly slate, but numerous diabase dikes cut the slate and are responsible for the several high falls along the course of the river some distance above and below the bridge. The road on the Canadian side follows roughly the course of the river and returns close to it at the Middle Falls. Beyond the Middle Falls the road angles away from the river, but a side road leads down to Pigeon Falls, the highest water fall in Minnesota. (See Figure 11.) A side trip to this point is well repaid.

THE GRAND PORTAGE[1]

The trail known as the Grand Portage crosses Highway No. 1 about a mile and a half from the Pigeon River. Long before white men visited the region, the Indians had utilized the trail as the best route connecting Lake Superior with the navigable portion of the Pigeon River. Its length is approximately nine miles. The numerous falls and rapids make the last twenty miles of the river impossible for navigation even by canoe.

The first white man to leave a record of the use of the portage was Sieur de la Verendrye, who crossed it in 1731, and referred to it as the Grand Portage. It is believed that a party of British traders visited the region in May, 1762, but due to the hostility of the Indians the occupation of the region was not permanent. By 1778 the portage was being utilized to a great extent and it was estimated that forty thousand pounds of goods were carried across every year. In 1778 the British sent a small detachment consisting of an officer and twelve soldiers to take charge of the area. The organization of the Northwest Company in 1783 opened up a period of great activity. A fort or stockade was built and several buildings were erected inside it at Grand Portage Bay. At the western end a stockade and other buildings, composing Fort Charlotte, were erected.

The land over which the portage ran became a part of the United States by virtue of the Treaty of 1783, but the British did not completely relinquish control until 1796. A new route was established by the Northwest Company with headquarters at Fort William, Ontario. This was some distance east of the mouth of the Pigeon River. From this time on the importance of the Grand Portage route decreased. By the Webster-Ashburton Treaty of 1842, it was provided that the portage should be free and open to the use of British, as well as American, citizens.

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[1] Condensed from The story of Grand Portage, by Solon J. Buck, Minn. History Bull., vol. 5, p. 20, 1923.

During much of the period of great activity the Grand Portage was a footpath only and all goods were carried across in packs. In 1788 a request by the Northwest Company for a grant of land to enable it to construct a wagon road was refused, but at a somewhat later date the trail was improved so that ox carts could be used. The trail still shows the ruts formed by the wagons.

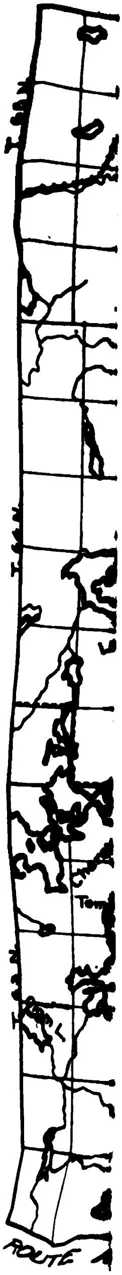
The Pigeon River in the general vicinity of Fort Charlotte is noted for its falls and deep gorge. Partridge Falls are about a mile and a half above the end of the portage and Split Rock Canyon and the Hairpin turn (see Plate VII B) are about a mile downstream from the portage. For those who enjoy a tramp, a trip over the Grand Portage Trail from the highway to the Pigeon River would make an ideal day. Sufficient time would be available for a visit to either, or possibly both, of the features mentioned above.

Route Map No. 12 shows the location of the various points mentioned above, including the Grand Portage Trail.

SIDE TRIP ON THE GUNFLINT TRAIL

As noted in the description of Grand Marais the Gunflint Trail starts at the town and follows a northerly route for twenty miles, thence runs westerly for about 20 miles more to Gunflint Lake. (See Maps 11, 12, and 13.) The auto road follows roughly the route of the old trail built when the Paulson iron mine just west of Gunflint Lake was being explored. With the exception of the first few miles the road passes through entirely unsettled country, much of which is within the Superior National Forest. (See Maps 12 and 13.) The drive is one of the most attractive found in the state. The northern half of the route touches many lakes from which canoe trips may be started. Canoes are available at Hungry Jack and Clearwater lakes. Camp sites are abundant all along the trail.

Leaving Grand Marais the road runs northward then eastward to ascend the hill at a convenient grade. A most picturesque bird's-eye view of the harbor and coast may be had from the road along the hill. About three miles from the town the road reaches the crest of the hill and drops to the valley of the Little Devil Track River in which there is a rolling area with much cleared land to the main Devil Track River. Outcrops of rhyolite and basalt flows and an intrusive diabase may be seen downstream from the bridge. The last settlement along the route is located around the small sawmill on the river. Beyond the river the road runs nearly due north for some distance over a fairly level area of gravel deposits. This is apparently the highest level of Lake Duluth (the glacial lake which occupied the Superior basin, see Figure 4, page 20), as within a mile or two glacial boulders become abundant and the gravel deposits are no longer conspicuous.


Tom
ROUTE

The country has been burnt over at a comparatively recent time to a point about ten miles north of Grand Marais. Just at the north border of the burnt area is a fine group of white pines through which the highway passes. This gives some idea of what the region was like before it was devastated by logging operations and fires.

The country along this part of the road is gently sloping, but farther north large ridges appear. Twelve miles north of Grand Marais red angular blocks of syenite are abundant along the road and to the east a ridge of this type of rock is found across a swamp from the road. This continues to the prominent hill which lies between the road and Northern Light Lake. This hill is gabbro much like that at Duluth and, as at Duluth, there is a gradation from gabbro to syenite, so that it is difficult, if not impossible, to determine where to draw the line between the two. The syenite or red portion is lighter than the black basic gabbro and the separation of the two is believed to be due to the action of gravity while the rocks were still practically molten. This is one of a group of exposures that occur at intervals from the Reservation River to Duluth.

Northern Light Lake is shallow and swampy, unlike most Minnesota lakes, but it is a favorite feeding ground for moose, and the traveler who climbs the ridge above the road may be rewarded by a glimpse of one feeding on the reeds. They feed in the early evening, as a rule. The southern boundary of the Superior National Forest is marked at the road side near the lake.

At Northern Light Lake there is a change in the type of trees. South of the lake the region is covered with a second growth consisting mainly of birch and poplar, but to the north these are displaced by a thick stand of jack pines with only a little poplar and birch.

To the northward the road passes through a decidedly hilly country, but only the larger hills are composed of solid rock, as the road cuts usually show only gravel. The South Branch of the Brulé River is in a shallow valley in glacial drift at the bridge and the road continues over a hilly gravel and boulder country. A few miles farther on the North Branch of the Brulé River is entrenched in a pronounced valley in glacial drift.

Somewhat more than a mile north of the river the road passes over a very marked boulder bed. This is apparently an old stream channel and the outline of the valley may be seen on both sides of the road. Presumably the stream washed away the fine silt and pebbles, but was unable to move the large boulders which are chiefly of red syenite. Two miles north of the river is an outcrop of very coarse syenite over which the road passes and a creek exposes the same rock in its bed. The size of the individual crystals or grains of orthoclase and plagioclase feldspar as well as of augite, vary from small grains to those an inch across. This is a somewhat basic phase of the syenite and it continues in variable phases for over a mile, then grades to normal gabbro.

Some distance beyond here a road turns off to the east to East Bearskin Lake, where the United States Forest Service has provided camp sites. The main road turns more to the northwest. Outcrops of gabbro are abundant up to and beyond the point where a road branches off to the right to Hungry Jack Lake. The main road angles to the left and follows the north shore of Poplar Lake. Here is an interesting outcrop of titaniferous iron ore or magnetite in the gabbro. This may be seen in the rough blocks blasted out for the road, and north of the road is an outcrop consisting mostly of titaniferous magnetite. These iron deposits have segregated in the gabbro at many places from Poplar Lake westward for fifty miles, but are particularly abundant in the region just described. The material has no value as ore at present, as the titanium content makes it difficult to smelt. Outcrops of gabbro are nearly continuous for several miles along Poplar and Pope lakes and titaniferous magnetite may be found in several limited areas. Scattered gabbro outcrops continue to Loon Lake. Here many graywacke boulders or angular blocks indicate the presence of the Rove slate formation. (See pages 13 and 86.) This formation bounds the gabbro on the north, but it is not well exposed along the route. The road swings northward around the west end of Loon Lake and touches Gunflint Lake at its west end.

The series of lakes which have been noted are only a few of the great number in this region (see Map 13), but any of them will give the traveler an idea of their attractiveness. By canoe, scores of lakes of all sizes may be reached by routes marked and kept open by the Federal and State Forest Service. To enjoy fully this magnificent lake country this mode of travel is recommended; the thrill of gliding silently along in these surroundings under the power of one's own strokes cannot be described.

OLD HIGHWAY NO. 1, OR THE INLAND ROUTE

Previous to the construction of the new road along the lake shore from Two Harbors to Cross River, the route of Highway No. 1 turned inland at Cross River at the east end, and on the Stewart River near Two Harbors at the other end. (See page 71.) The road follows the uplands and is located at places as much as ten miles inland. Many streams offer excellent trout fishing and the country is of a somewhat different type from that close to Lake Superior. It is probable that many will wish to follow this route on the return trip and for this reason a few notes on this country are included.

From Cross River (see Route Map No. 10) the old road trends about due west nearly to the line between Cook and Lake counties. There it turns one-half mile south, then west again. For the first mile and a half the road ascends a steep grade and outcrops of basalt flows occur here and there, while a fine view of the coast may be had to the south. The road then reaches a more nearly level country and hills cut off the view of the lake. This area along the road is burnt over to a point within a mile east of the county line. There the road passes into a partially cut-over forest, where a thick growth of maple and birch renders the country far more attractive than the burnt-over regions.

A mile west of the county line the road enters a big valley with high hills beyond. One of these hills is conspicuously white, which suggests that it is composed of anorthosite and this is found on examination to be the case. The road descends into the valley which is occupied by the Caribou River and its branches and thence turns southward to cross a big diabase ridge at a low spot. Thence it descends to the valley of one of the branches of the Manitou River. The village of Cramer is located where the road turns nearly due south. The country about Cramer is extremely rugged. High diabase ridges have been dissected by the swiftly flowing streams of the region. Beyond Cramer the road follows an irregular southwestward course to Finland and much of the way parallels the abandoned grade of the Duluth and Northern Minnesota Railway. The road crosses the Manitou River about two miles southwest of Cramer. Below the road the river has cut a deep gorge. Beyond the Manitou the road passes over a divide and runs not far from a branch of the Baptism River to Finland. Midway between Cramer and Finland the road swings northwestward away from the river and passes over a morainic hill covered with a heavy growth of hardwood. Near Finland the road swings back to the river. The rock outcrops consist mainly of diabase and basalt.

From Finland a branch road extends northwest to Ely on the Vermilion Iron Range. A good road also connects with Highway No. 1 at Little Marais.

From Finland south and westward the country is somewhat less rugged for about three miles, then becomes very rugged again and many conspicuous hills of anorthosite occur, mainly south and east of the road. They are especially numerous just east of Lax Lake. The road follows the north shore of Lax Lake, then turns south at its west end and continues nearly due south to the Beaver River two miles from Beaver Bay. The main rock of the region is the Beaver Bay diabase (see page 73), which with the anorthosite masses included in it, is responsible for the hills and ridges. Near the junction of the east and west branches of the Beaver River the road turns west and follows the gorge of the west branch. Then it gradually enters a more level country and crosses the west branch, where it flows in a shallow valley. From this point to Two Harbors the country near the road is not rugged and few outcrops are found. The road gradually seeks lower levels, and steep grades such as the one where the road turns inland at Cross River are no longer encountered.

CHAPTER VIII

FISH AND GAME ALONG HIGHWAY NO. 1[1]

THADDEUS SURBER

Game and Fish Department

SOUTH STATE LINE TO THE TWIN CITIES

The extreme southern part of Minnesota is so extensively cultivated that it is only in favored localities that fish and game still prevail in any quantities. Almost due east from Albert Lea near Spring Valley, on the many spring tributaries of the Root River, good brook trout and brown trout fishing is still to be found and this is true also of the smaller tributaries to the Whitewater River east of Rochester, which may be easily reached by a side trip from Owatonna. However, those desirous of fishing for small-mouthed bass can find good sport in the Red Cedar River near Austin; while good, big-mouthed bass fishing is found in many of the lakes around Albert Lea and to the northward of that point at Faribault. Small-mouthed bass may be obtained at certain times in the Straight River between Faribault and Owatonna, but the best fishing in that vicinity is for large-mouthed bass and pike in the many lakes to the west and northwest of Faribault, particularly Shields, French, and Tetonka lakes. It is possible to find good fishing for bass, crappies, and sunfish and, at times, for wall-eyed pike, in the Cannon River, particularly in that widening of the Cannon known as Byllesby Lake near Cannon Falls. A number of the little spring feeders of the Minnesota River about Savage and other points between Shakopee and St. Paul afford angling for brook and rainbow trout. In fact, about the only rainbow trout found in southern Minnesota occur in some of these small streams.

The game of the region south of the Twin Cities consists of bobwhite in the extreme southeastern counties of the state, with considerable numbers of prairie chickens in favored localities, but the best shooting is obtained during the fall migration of the ducks when excellent sport is furnished on the passes between many of the lakes from Albert Lea northward, particularly those lakes in the vicinity of Faribault. Cottontail rabbits and squirrels occur almost everywhere, but squirrels are more abundant in the country near the Mississippi River eastward of Highway No. 1, where the heavy timbered bluffs supply them necessary food and refuge.

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[1] Most of the streams and lakes referred to will be found on the route maps (Nos. 1-13).

TWIN CITY REGION

In the vicinity of the Twin Cities, notwithstanding the tremendous drain made on the lakes, excellent fishing for bass, sunfish, and wall-eyed pike is still to be had within a few miles, notably at White Bear and Lake Minnetonka. A side trip to Stillwater can be taken and in addition to the species of fish taken in the vicinity of the Twin Cities, anglers will find good fishing for small-mouthed bass in the St. Croix River and Lake St. Croix, and will, at certain seasons, be able to procure great numbers of the white bass, one of the most beautiful of fresh water fishes.

Twin City anglers find the best of trout fishing on the Wisconsin side not far from Hudson; some of the smaller tributaries of the St. Croix abounding in brook and brown trout.

TWIN CITIES TO DULUTH

Traveling northward from the Twin Cities good fishing is to be had in almost every lake encountered along the highway but the best fishing is to be obtained by a side trip through the Chisago chain of lakes to Taylors Falls, though the fishing at Forest Lake is of the best. However, when one becomes satiated with bass and crappie fishing in the Chisago lakes he can proceed to Taylors Falls and there fish for the so-called muskellunge, and for wall-eyed pike, in the St. Croix River in that vicinity. Returning to the main highway and proceeding northward, the Snake River at Pine City, together with Cross Lake and Pokegama Lake, afford good sport for the angler, practically all the native game fishes being taken there. In this connection it is well to state that it is possible for the angler occasionally to obtain a sturgeon in Lake Pokegama.

At Hinckley a side trip should be made eastward into the State Game Refuge (it is five miles to the west boundary), not only for the purpose of seeing the deer and partridge, which occur there in such great numbers, but also to enjoy the trout fishing, which may be had in the eastern part of this refuge. Such creeks as Hay Creek, Bangs Brook (these are 24 and 20 miles, respectively, due east of Hinckley), and others, are noted trout streams and are steadily maintained as such by the state, providing good fishing for both brook and brown trout, but particularly for brook trout.

In the Kettle River, which forms the western boundary of the refuge, small-mouthed bass abound and will repay anyone for the inconvenience of a trip by boat or canoe down this river and the St. Croix back to Taylors Falls. Not only will the angler be well repaid in the small-mouth bass fishing but he will also, under favorable conditions, be able to procure a goodly number of wall-eyed pike.

PLATE VIII

COMMON GAME FISHES OF MINNESOTA

In order from top to bottom

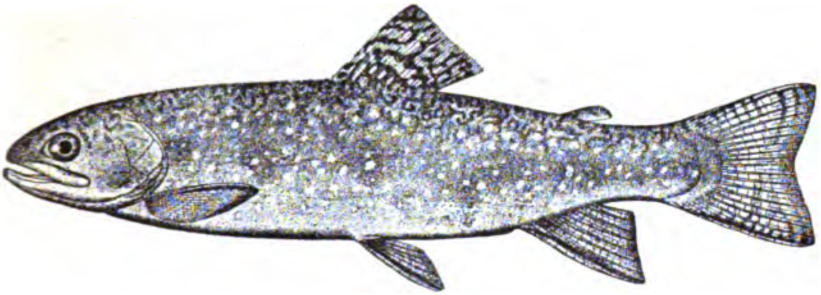
A. Brook trout. Speckled trout. *Salvelinus fontinalis.*

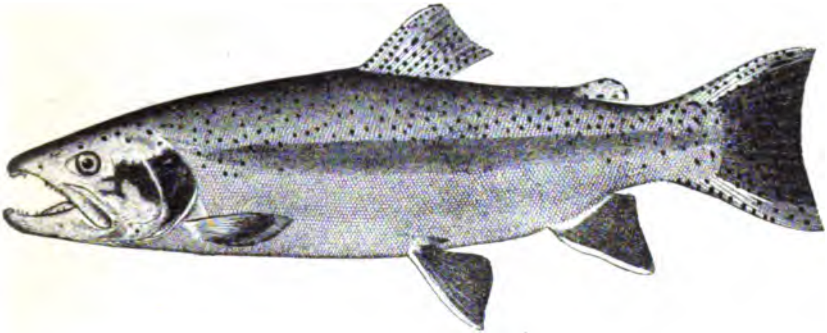
B. Rainbow trout. *Salmo irideus.*

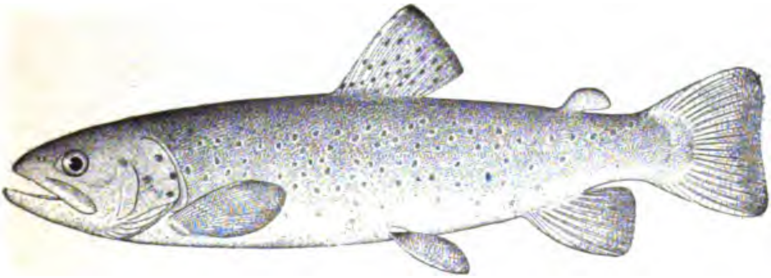
C. Brown trout. German brown trout. *Salmo fario.*

D. Lake trout. Mackinaw trout. *Cristivomer namaycush.*

PLATE VIII







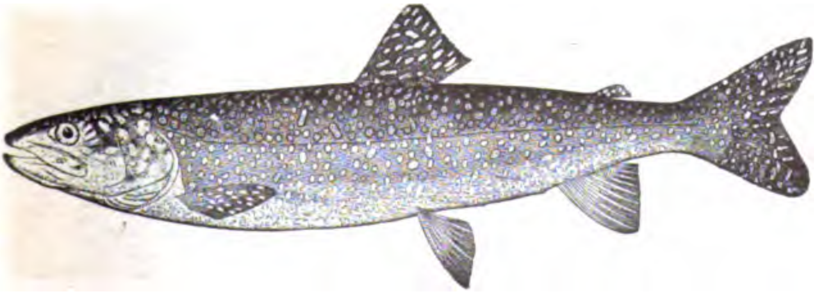


PLATE IX

COMMON GAME FISHES OF MINNESOTA

In order from top to bottom

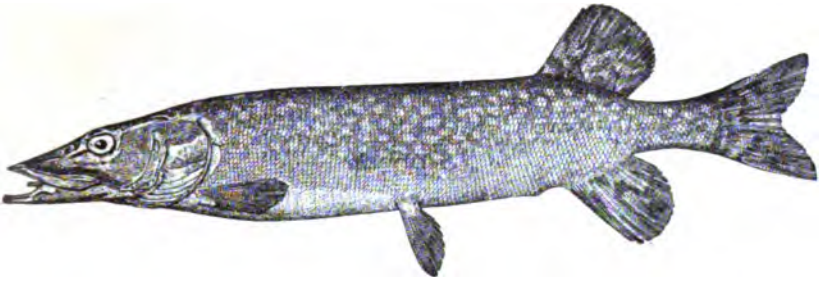
A. Pike. Great northern pike. Northern pickerel. Jackfish. *Esox lucius.*

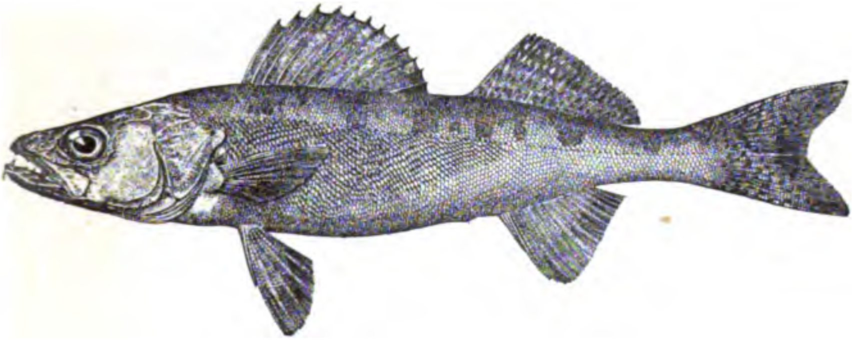
B. Pike-perch. Wall-eyed pike. Yellow pike. *Stizostedion vitreum.*

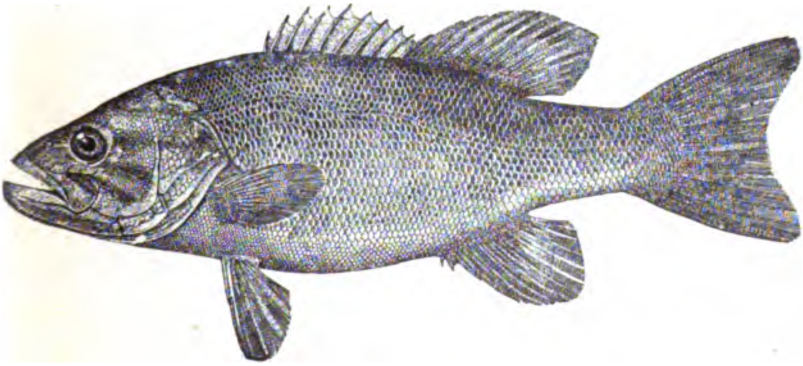
C. Small-mouthed bass. River bass. *Micropterus dolomieu.*

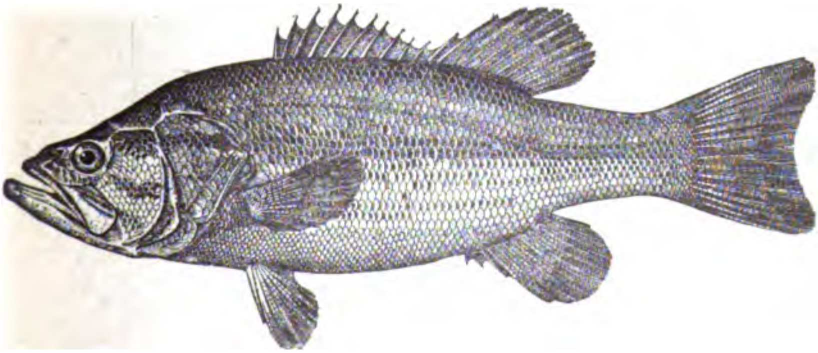
D. Large-mouthed bass. Black bass. Green bass. *Micropterus salmoides.*

PLATE IX









In the territory between St. Paul and Hinckley there are prairie chickens and, in the timbered areas, a considerable number of partridge, or ruffed grouse, while to the northward of the Pine County Refuge in the country along the road leading from Sandstone eastward to the Wisconsin line, good deer hunting is always to be had in season. This is made possible because of the overflow from the Pine County Refuge which lies to the southward. With the exception of the pike and bass fishing in Sturgeon Lake, there is really very little fishing to be obtained in the country between Hinckley and Carlton, but to the eastward of the main highway in Pine and Carlton counties, probably more sharp-tailed grouse can be found at this time than in any other like area in the entire state of Minnesota. This country is very rolling, has been burned over repeatedly, and is now growing up in just that character of country that seems to supply these birds with the proper living conditions, and they appear literally by the thousands in this particular country, while partridge are found everywhere in the ravines and in the wooded swamps between Carlton and Duluth. A number of small spring-fed streams still support a goodly number of trout, which are being maintained by the state. Tributaries of the Moose River in Carlton County furnish excellent fishing for brook trout near the headwaters.

DULUTH AND THE NORTH SHORE OF LAKE SUPERIOR

In the vicinity of Duluth there are a number of lakes which afford good fishing for wall-eyed pike, but the streams from Duluth northeast to the Canadian border are essentially trout streams, while the lakes, unless stocked by the state or Federal government, very seldom have any bass in them. Lake fishing, therefore, is not nearly so popular as stream fishing until the deeper lakes in Cook County are reached, so that the prime consideration to the traveler is the condition of the streams north and eastward of Duluth. Streams near Duluth, or between Duluth and Two Harbors, are fished so persistently that they are not very inviting to the casual angler, but to the eastward of that city many first-class trout streams exist. It must be clearly understood, however, that the best trout fishing in any of these streams is not obtained in the immediate vicinity of the highway, but the angler, to obtain the best fishing, must penetrate two or three miles up or down stream, as the case may be, and be prepared to fight brush and mosquitoes. Results well repay the hardships of those who make these short excursions.

While all the streams crossed by the highway, with the exception of the Temperance River, afford more or less good angling for brook trout, the best streams between Two Harbors and Grand Marais are the Gooseberry, the east and west branches of the Beaver River near Beaver Bay, the various branches of the Baptism, except the east branch at Finland, the Manitou River, and Nine Mile Creek near Cramer. On the headwaters of the Baptism and Manitou in particular, fine brook trout may be obtained, while an excursion down stream on both of these rivers will well repay the angler in the early part of the season, May and June. Passing eastward from Cramer the first stream encountered is the Caribou. Both above and below the road crossing, extending upward to the beaver dam on the headwaters, will be found good brook trout fishing. East of this the next stream encountered is the Two Island River, but this stream will have to be fished upstream for best results; the trout, while they occur in considerable numbers, are found most commonly in the upper stretches of this stream where the thickets are most dense along its banks. The next stream to be encountered is the Cross River, which both the old and new highways cross near its mouth; certain stretches of this stream provide good fishing, while other stretches do not. One of the best points at which to fish is just above and below where the Four Mile Creek empties into it from the west side, a few miles out of Schroeder. Just east of Schroeder the Temperance River is crossed but need, at the present time, be given little consideration by the casual traveler, as it is not a trout stream. However, the state has recently introduced in its waters small-mouthed bass and it is hoped that within a few years excellent fishing will be obtained for this species in this river. North and east of this comes the Onion River, a small stream which affords no fishing near its mouth, but its upper waters abound in brook trout. If one has the stamina to reach the upper waters he is usually repaid with a full creel.

The Poplar River, which enters Lake Superior at Lutsen, is fed by an enormous number of lakes and has so much dead water that during the summer months it affords no suitable waters for trout, except for two miles above Lutsen, where it is spring fed. At certain times good catches of trout, both brook and brown, are taken between Lutsen and the old mill three miles above, but this stream cannot be relied on for trout fishing. The lakes north of Lutsen furnish excellent angling for great northern pike and other fishes of that character and will repay a visit for the observation of big game which will be referred to later on. Some distance east of Lutsen and about four miles west of the Cascade, a small stream crosses the road which might be ignored by the casual as too small for consideration as a trout stream. This is known as Spruce Creek and is one of the best small streams along the north shore for brook trout, but is a very difficult stream to fish because it is small and passes through very heavy forest with dense undergrowth. The Cascade is next reached, being the last stream of any size between Two Harbors and Grand Marais. This is perhaps one of the most noted trout streams on the north shore and affords very fine trout fishing to those who care to wade and fish the stream as it should be fished. The main highway crosses it at the mouth, but by going eastward to Good Harbor Hill schoolhouse and there taking the road back to the westward (see Map No. 11), the stream can be reached several miles above its mouth at a point where suitable camping grounds can be had, and the stream may be fished both above and below this road on the best trout waters. The upper Cascade becomes very warm during the summer and is therefore unsuitable for trout but some tributaries entering from the east, notably Blackwell or Bally Creek, and two other unnamed tributaries, abound in brook trout during the entire summer.

GUNFLINT TRAIL

At Grand Marais is opened up a vast territory of lakes to the northwestward along the Gunflint Trail, but before reaching these lakes two trout streams demand attention, both a short distance north of town. These are the Little Devils Track and Devils Track rivers. The Little Devils Track usually supplies good angling for brook trout to its source, but it is useless to expect good fishing in the Devils Track west of the Gunflint Trail because it is fed by large lakes a short distance above and these have a tendency to warm the water to such an extent that it makes the water higher up uninhabitable for trout. This is true also of the north and south branches of the Brulé which is crossed farther north. Both these streams, however, are being stocked with small-mouthed bass and it is hoped that in the near future these will prove great attractions to anglers. Nearly all of the lakes north of Grand Marais toward the Canadian border, as well as hundreds of lakes lying to the east and west, are very deep and most of them have great numbers of lake trout in their waters. If the season is a cold one these lake trout can be taken by ordinary angling in comparatively shallow water through almost all the summer, but if it is a hot season then angling at a greater depth is imperative if good catches are to be made. In all of these lakes the great northern pike abound. Being fish of superior quality, great fighters, and of great size, they afford most excellent sport to those who care to troll for them. Unfortunately no wall-eyed pike are found in any of the lakes or streams tributary to Lake Superior, but as soon as the watershed to the westward is crossed into waters flowing towards Rainy River and Hudson Bay, one finds the lakes teeming with wall-eyed pike. To reach this fishing it is necessary to take a canoe journey from the Gunflint Trail to Ely or International Falls. In the majority of these lakes whitefish are found, but these are not an angler's fish and are, therefore, given very little consideration at this time, though they are of great commercial value.

SHORE EAST OF GRAND MARAIS

Eastward of Grand Marais the first trout stream of any importance beyond the Devils Track River is Kimball Creek. The headwaters of Kimball Creek may be reached from the Gunflint Trail and fished downward, or one can walk from the main highway to the point above the falls and fish upstream, in either event with the assurance that fair catches will be made. This is also true of the next creek to the eastward, Kadunce Creek, which probably has its source in Trout Lake and is a very good stream for trout fishing above the falls. Both Kadunce and Kimball creeks may be reached by old trails, as before stated, leading in from the Gunflint Trail or by other trails leading up from Highway No. 1. After passing Kadunce Creek the next stream to be encountered is the Brulé River. As noted above the upper part of the Brulé is not suitable for trout, and attempts are now being made to stock it with small-mouthed bass, but for three or four miles above its mouth both the main stream and two or three small tributaries have a considerable number of trout, mostly brook trout, in their waters, and at times afford fairly good fishing. Passing eastward the next stream one encounters is Flute Reed Creek, which enters Lake Superior in Big Bay at Hovland. This stream has a number of tributaries, and while all are small a fair number of brook trout are found in favored pools and these at times afford fairly good fishing. Passing eastward towards the border one comes to the last trout stream of any importance at the Reservation River, which is crossed just east of Big Bay. This is one of few streams along the north shore where trout can pass upwards from Lake Superior to the headwaters without serious obstruction in the way of falls, and consequently the fishing is not only maintained from Reservation (or Swamp) Lake and Trout Lake, but is also materially assisted by migration from Lake Superior; therefore, the fishing is generally excellent throughout the season. However, the largest trout are usually caught in Trout Lake which can be reached by a blazed trail from Mile Post 30 between Big Bay and Mineral Center.

The Pigeon River on the international boundary line between Minnesota and Ontario is mainly interesting for its scenic features and not as a fish stream. Insurmountable falls at its mouth preclude the passing upward of trout from Lake Superior and it is doubted, even though it were stocked with trout, whether they could be maintained there because of the warm temperature of its waters during summer months. With the exception of the Reservation River, before mentioned, all the streams tributary to Lake Superior are inaccessible to trout from Lake Superior because of high falls at their mouths. This very fact at times creates good angling at the mouths of these rivers for such species as steelheads and brown trout and the fact that steelheads are caught about the mouths of all these rivers demands attention from the enthusiastic angler because all realize that this one of the gamest fish which have been introduced from other sections of the United States. They are thriving in great numbers in Lake Superior and will no doubt in time become more important. During certain periods of the summer good lake trout fishing can be had in the very small bays along the north shore by trolling, notably in the bays at Grand Marais and at Grand Portage.

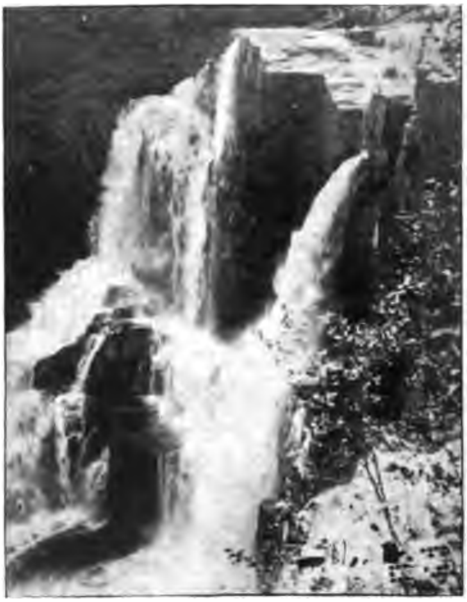


FIGURE 10. PIGEON FALLS

GAME ALONG THE NORTH SHORE

Game conditions north and east of Duluth in St. Louis, Lake, and Cook counties, are of as great importance as its fish life. The summer tourist by merely traveling along the road during the early part of the season will often run across deer, black bear, and moose, and if he should happen to be an enthusiastic photographer a side trip out of Cramer or Lutsen into the lake region near the Superior Game Refuge will well repay him in the chances he will have to secure pictures of moose and deer, particularly moose.

One of the most noted localities during the early summer months is the lake region which feeds the Poplar River directly north of Lutsen, and a lake to the westward of this known as Four Mile Lake on the old abandoned Duluth and Northern Minnesota Railway. It never fails to give a photographer an opportunity to use a camera. Four Mile Lake, however, at the present time, is more or less isolated and can only be reached by a road leading north from the inland highway just east of the Caribou River, to the old railroad grade. From there it will be necessary to walk six or seven miles to the Four Mile ranger station in order to reach this moose territory. To the sportsmen the entire region has a great attraction. While the moose are now protected indefinitely, so far as hunting them is concerned, during the open season good deer hunting can be had anywhere between Two Harbors and the border. In the country north and east of Duluth, and north of Two Harbors, where it has been more or less settled and the country opened up, great numbers of sharp-tailed grouse and a few prairie chickens are found at the present time, while partridges are so numerous, even along the highway, that one often wonders where they all come from. Snowshoe rabbits are found everywhere throughout that region, but the cottontail rabbit has not as yet penetrated much beyond Duluth. It will do so when the country is more generally developed and the original forest removed.

CHAPTER IX

TREES AND PLANTS ALONG HIGHWAY NO. 1

C. OTTO ROSENDAHL AND FREDERIC K. BUTTERS

NOTE.—The figures refer to footnotes in which the common forms of plant life are listed for each type of vegetation.

That part of Minnesota lying near this highway as far north as Faribault was originally largely prairie country with scattered groves along the streams and to some extent on the uplands. It happens, however, that the course taken by Highway No. 1 lies very largely through these groves.

The country has of course been greatly modified by farming operations which have cleared away large parts of the natural woodland while at the same time the farmers have planted groves and woodlots in districts that were originally prairie. It is still possible, however, to distinguish the two types of country. The remnants of natural groves contain a great many oaks. The trees are of all ages and sizes and, where they have not been used for pastures, there is a considerable undergrowth of shrubs and native flowering herbs.[1] Planted woodlots show their origin by the regular

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[1] The most common and characteristic shrubs of the groves and thickets along the highway from the southern boundary of the state to Faribault are: hazelnut—*Corylus americana*, wild plum—*Prunus americana*, choke cherry—*Prunus virginiana*, western crab apple—*Pyrus ioensis*, June berry—*Amelanchier canadense*, wild thorn—*Crataegus punctata*, glandular thorn—*Crataegus rotundifolia*, red raspberry—*Rubus strigosus*, blackberry—*Rubus allegheniensis*, wild rose—*Rosa blanda*, Missouri gooseberry—*Ribes gracile*, prickly gooseberry—*Ribes Cynosbati*, wild black currant—*Ribes floridum*, staghorn sumac—*Rhus typhina*, smooth sumac—*Rhus glabra*, poison ivy—*Rhus toxicodendron*, prickly ash—*Zanthoxylum americanum*, black haw—*Viburnum Lentago*, panicled dogwood—*Cornus paniculata*.

The following vines are also common: wild grape—*Vitis vulpina*, bittersweet—*Celastrus scandens*, woodbine or Virginia creeper—*Psedera quinquefolia*.

The herbaceous undergrowth is made up mostly of the following species arranged according to seasons. Spring flora: bloodroot—*Sanquinaria canadensis*, hepatica—*Hepatica acutiloba*, Dutchman's breeches—*Dicentra cucullaria*, wild ginger—*Asarum canadense*, bellwort—*Uvularia grandiflora*, meadow rue—*Thalictrum dioicum*, columbine—*Aquilegia canadensis*, jack-in-the-pulpit—*Arisaema triphyllum*, nodding wake-robin—*Trillium cernuum*, woolly blue violet—*Viola sororia*, yellow violet—*Viola pubescens*.

Summer flora: Wild crane's-bill—*Geranium maculatum*, Solomon's seal—*Polygonatum commutatum*, false Solomon's seal—*Smilacina racemosa*, *Smilacina stellata*, wild sarsaparilla—*Aralia nudicaulis*, yellow pimpernel—*Pimpinella integerrima*, sweet cicely—*Osmorhisa Claytoni*, yellow avens—*Geum strictum*, white avens—*Geum canadense*, hairy agrimony—*Agrimonia gryposepala*, showy tick-trefoil—*Desmodium canadense*, tall anemone—*Anemone virginiana*, snakeroot—*Sanicula marilandica*, American gromwell—*Lithospermum latifolium*, Virginia stickseed—*Lappula virginiana*, hare figwort—*Scrophularia leporella*, Culver's-root—*Veronica virginica*, robin's plantain—*Erigeron pulchellus*, slender wild rye—*Elymus virginicus*, bottle-brush grass—*Asprella Hystrix*, panic grass—*Panicum latifolium*, brome grass—*Bromus purgans*.

Autumn flora: Stiff-haired sunflower—*Helianthus hirsutus*, wood sunflower—*Helianthus strumosus*, starved aster—*Aster lateriflorus*, arrow-leaved aster—*Aster sagittifolius*, blue wood aster—*Aster cordifolius*, Canada goldenrod—*Solidago canadensis*, zigzag goldenrod—*Solidago latifolia*.

Roadside vegetation: Very little of the original flora remains along the roadsides on account of the natural conditions having been disturbed repeatedly. Its place has been taken by hardy an-arrangement and frequently by the uniform size of the trees. They almost never contain oaks, the commonest trees being cottonwoods, willows, and soft maples. They seldom have much undergrowth except the common introduced weeds, but in some of the older ones shrubs and flowers of the native forest have intruded. In practically no part of this region does one see any remnant of the old native upland prairie vegetation, except occasional fragments along railroad rights-of-way. In contrast to this the original vegetation of meadowlands and marshes[2] has remained almost unchanged except where drainage operations have transformed the character of the habitat.

From the southern boundary of the state as far north as Geneva Lake, the road passes through a succession of groves of the "oak-opening" type and to a considerable extent the original parklike type of landscape still persists. These groves are largely made up of scarlet oak, bur oak, American elm, and aspen. In the spring the landscape is beautified by such flowering trees and shrubs as wild plum, wild crabapple, black cherry, choke cherry, black haw, June berry, and thornapple.

Immediately to the east and southeast of Lake Geneva there was originally a vast marsh, which has been recently reclaimed by drainage operations and transformed into a very progressive farming community. In this marsh there were two small islands known respectively as Maple Island and Hickory Island. The former supports a heavy growth of hard maple, basswood, and elm such as is found much more commonly

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mostly introduced weeds among which the following species are the most abundant and widespread: quack grass—*Agropyron repens*, squirreltail grass—*Hordeum jubatum*, lamb's quarters—*Chenopodium album*, pigweed—*Amaranthus retroflexus*, knot-grass—*Polygonum aviculare*, wild buckwheat—*Polygonum convolvulus*, artichoke—*Helianthus tuberosus*, common ragweed—*Ambrosia artemisiifolia*, giant ragweed—*Ambrosia trifida*, wild lettuce—*Lactuca canadensis*, prickly lettuce—*Lactuca scariola*, common plantain—*Plantago major*, nettle—*Urtica gracilis*, shepherd's-purse—*Capsella Bursa-pastoris*, pepper-grass—*Lepidium apetalum*, burdock—*Lappa minor*, bull thistle—*Cirsium lanceolatum*, field thistle—*Cirsium discolor*, cocklebur—*Xanthium canadense*, dandelion—*Taraxacum officinale* and *Taraxacum erythrospermum*.

[2] Marsh and meadow vegetation: The marsh vegetation is composed largely of sedges, bulrushes, and grasses of which the chief species are: bulrush—*Scirpus validus*, *Scirpus cyperinus*, *Scirpus atrovirens*, *Scirpus fluviatilis*, sedges—several species of *Carex* and *Cyperus*, spike rush—*Eleocharis palustris*, cotton grass—*Eriophorum*, slough grass—*Spartina Michauxii*, wild rice—*Zizania aquatica*, reed—*Phragmites communis*, together with the following: cat-tail—*Typha latifolia*, bur-reed—*Sparganium eurycarpum*, water plantain *Alisma plantago-aquatica*, arrowhead—*Sagittaria latifolia*, sweet flag—*Acorus calamus*.

The most characteristic and conspicuous plants of the moist meadows during late spring and early summer are: marsh marigold—*Caltha palustris*, saxifrage—*Saxifraga pennsylvanica*, violets—*Viola papilionacea*, blue flag—*Iris versicolor*, golden ragwort—*Senecio aureus*, water hemlock—*Cicuta maculata*, swamp milkweed—*Asclepias incarnata*, turk's-cap lily—*Lilium superbum*, Canada anemone—*Anemone canadensis*. Later in the season in the same situations appear blue vervain—*Verbena hastata*, joe-pye weed—*Eupatorium purpureum*, boneset—*Eupatorium perfoliatum*, false dragon head—*Physostegia virginiana*, turtle head—*Cheolne glabra*, sneeze weed—*Helenium autumnale*, asters—*Aster prenanthoides*, *Aster paniculatus*, *Aster puniceus*, boltonia—*Boltonia asteroides*, beggar's ticks—*Bidens frondosa*, *Bidens cernua*, great lobelia—*Lobelia siphilitica*, and fringed gentian—*Gentiana crinita*.

in the central part of the state. Until the draining of the marsh it was so inaccessible that it remained practically in its original condition, but it is now being converted rapidly into farming land. The other island lying about a mile further south has been inhabited for many years, but it is still largely covered with forest made up in great part of shellbark hickory, the western outpost of this species in Minnesota.

In the vicinity of Ellendale the road passes through a region which was originally prairie but thence northward to Owatonna it traverses the groves bordering the east bank of the Straight River. In the vicinity of Owatonna black walnut occurs in several localities, the only places where it is to be seen in the vicinity of this highway.

From Owatonna to Faribault the highway runs partly through upland prairie to the west of the Straight River and partly through the belt of hardwood timber which follows that stream. This forest is denser on the east side of the river, but even along the highway it shows more diversity than the groves further south.

From Faribault to Northfield the highway traverses the southeast corner of the great forest tract known to the early settlers as the "Big Woods."[3] This was a solid forest of mixed hardwoods which extended from here westward to Mankato and northward to St. Cloud. The original timber has been largely cleared in the vicinity of the highway, but there are still to be seen individual trees of hard maple, basswood, white and red elm, and red oak. The fine growth of hard maples in the city of Northfield is particularly to be noted. In this region there was the rather unusual phenomenon of a heavy forest lying to the *westward* of the Cannon River, while to the *eastward* of this stream there were extensive open prairies beginning a mile or so back from the river banks. This phenomenon is correlated with the difference in soil and topography of the two regions—the geologically very recent glacial drift, and diversified topography to the west, and the much older and less broken country to the east.

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[3] "Big Woods" vegetation. Shrubs: In addition to the shrubs already listed as characteristic of the groves and copses farther south there occur in this region: alternate-leaved dogwood—*Cornus alternifolia*, round-leaved dogwood—*Cornus circinata*, burning bush—*Euonymous atropurpureus*, Missouri gooseberry—*Ribes gracile*, iron wood—*Ostrya virginiana*, honeysuckle—*Lonicera dioica*.

Herbaceous undergrowth: Most of the woodland herbaceous plants already enumerated reappear throughout this region together with the following additions: Spring flora: dogtooth violet—*Erythronium albidum*, blue cohosh—*Caulophyllum thalictroides*, baneberry—*Actaea rubra*. blue phlox—*Phlox divaricata*, buttercup—*Ranunculus septentrionalis*, white violet—*Viola rugulosa*, bishop's cap—*Mitilla diphylla*, wild leek—*Allium tricocoum*, waterleaf—*Hydrophyllum virginicum*.

Summer vegetation: Solomon's seal—*Polygonatum commutatum*, *Polygonatum biflorum*, false Solomon's seal—*Smilacina racemosa*, black snakeroot—*Sanicula gregaria*, wild sarsaparilla—*Aralia nudicaulis*, spikenard—*Aralia racemosa*, yellow lady's slipper—*Cypripedium pubescens*, sweet cicely—*Osmorhiza Claytoni*, tick-trefoil—*Desmodium grandiflorum*, enchanter's nightshade—*Circaea lutetiana*, lop seed—*Phryma leptostachya*, maiden-hair fern—*Adiantum pedatum*, Virginia grape fern—*Botrychium virginianum*, lady fern—*Athyrium angustum*, shield fern—*Dryopteris spinulosa*

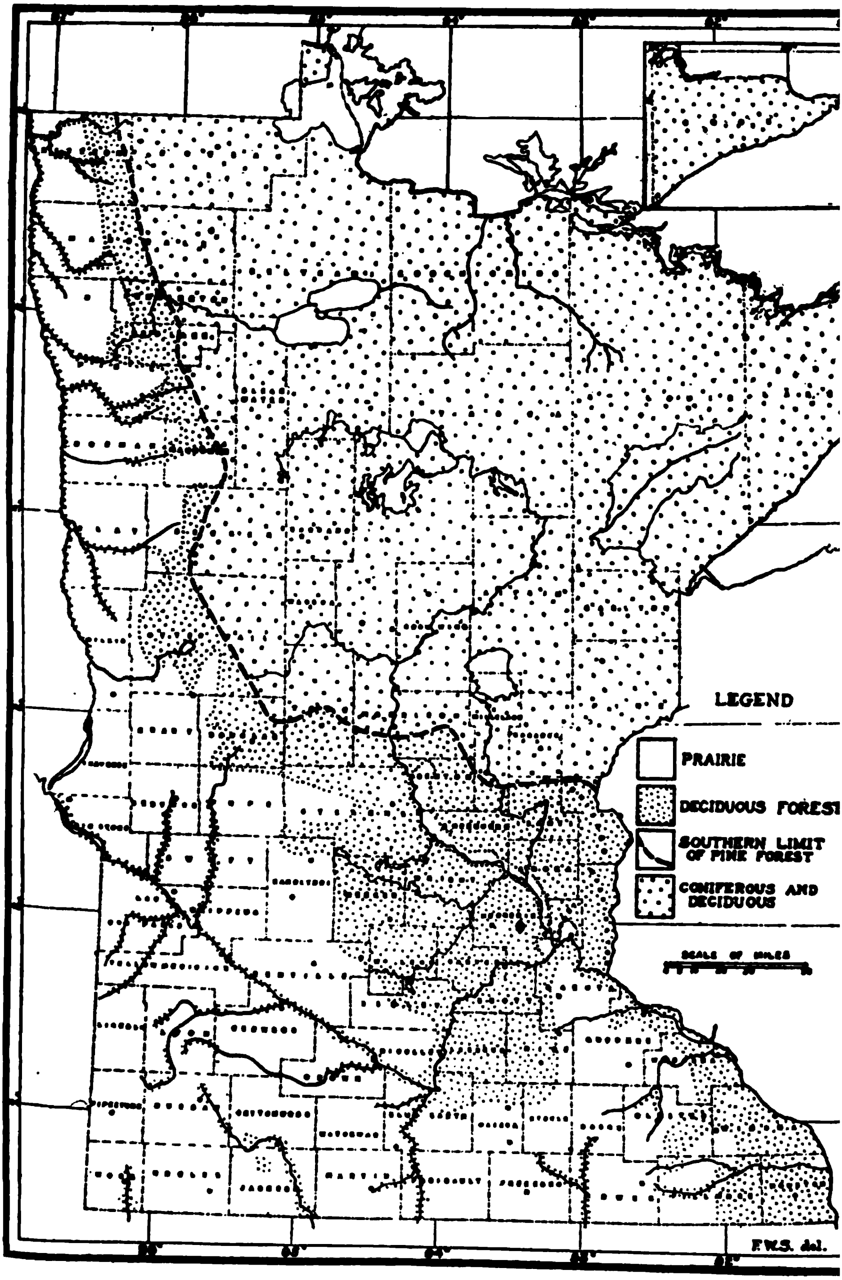

FIGURE II. MAP OF MINNESOTA SHOWING DISTRIBUTION OF FOREST AND PRAIRIE. AF
WARREN UPHAM AND FREDERIC K. BUTTERS

Leaving Northfield the highway almost immediately passes out of the eastern edge of the Big Woods and as soon as it turns northward away from the Cannon River it enters a tract of pure prairie which extends as far as Rosemount. Much of this is of course cultivated and has completely lost its original character, but on the sandstone knolls to the east of Castle Rock village there are still remnants of the original dry prairie vegetation.[4] Just north of Rosemount the highway passes abruptly from the prairie into a wooded district which originally extended unbroken to the Mississippi River. In contrast to the Big Woods this woodland is composed mostly of oaks and this is the first place along the highway where the white oak becomes an abundant tree.[5]

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[4] Vegetation of the prairie and sandy ridges, Northfield to Rosemount. Remnants of the original prairie vegetation are found on the ungraded embankment along the roadside, on the sterile sandy ridges and particularly along the railroad right-of-way where conditions have not been disturbed.

Spring flora: pasque flower—*Anemone patens,* hoary puccoon—*Lithospermum canescens,* bird's foot violet—*Viola pedata,* prairie violet—*Viola pedatifida,* ground plum—*Astragalus caryocarpus,* lady's-tobacco—*Antennaria neglecta,* prairie crowfoot—*Ranunculus rhomboideus,* blue-eyed grass—*Sisyrinchium campestre,* purple avens—*Geum triflorum,* lousewort—*Pedicularis canadensis,* bastard toadflax—*Comandra umbellata.* Shrubs: prairie willow—*Salix humilis,* sand cherry—*Prunus pumila.*

Summer flora: hairy puccoon—*Lithospermum Gmelini,* alum root—*Henchera hispida,* beard tongue, *Pentstemon grandiflorus,* golden meadow parsnip—*Ziria aurea,* western red lily—*Lilium philadelphicum,* larkspur—*Delphinium Penardi,* spiderwort—*Tradescantia bracteata,* anemone—*Anemone cylindrica,* spiked lobelia—*Lobelia spicata,* prairie phlox—*Phlox pilosa,* strawberry—*Fragaria virginiana,* tall cinquefoil—*Potentilla arguta,* butterfly weed—*Ascelepias tuberosa,* wild bergamot—*Monarda fistulosa,* flowering spurge—*Euphorbia corollata,* purple prairie clover—*Petalostemum purpureum,* white prairie clover—*Petalostemum candidum.* Among the more common grasses are porcupine grass—*Stipa spartea,* koeleria—*Koeleria cristata,* wheat grass—*Agropyron tenerum,* June grass—*Poa pratensis.* The following shrubs are also frequent: prairie rose—*Rosa pratincola,* lead plant—*Amorpha canescens,* New Jersey tea—*Ceanothus americanus,* wolfberry—*Symphoricarpos occidentalis.*

Autumn flora: The late summer and autumn prairie vegetation is gay with asters, goldenrods, and other members of the thistle family among which the commonest species are: field goldenrod—*Solidago nemoralis,* Missouri goldenrod—*Solidago missouriensis,* Canada goldenrod—*Solidago canadensis,* stiff-leaved goldenrod—*Solidago rigida,* slender showy goldenrod—*Solidago rigidiuscula,* velvety goldenrod—*Solidago mollis,* sky-blue aster—*Aster azureus,* smooth aster—*Aster laevis,* silky aster—*Aster sericeus,* white wreath aster—*Aster multiflorus,* oxeye—*Heliopsis scabra,* black-eyed Susan—*Rudbeckia hirta,* cone flower—*Lepachys pinnata,* stiff sunflower—*Helianthus scaberrimus,* Maximilian's sunflower—*Helianthus Maximilianus,* prairie sunflower—*Helianthus petiolaris,* blazing star--*Liatris scariosa,* stiff tickseed—*Coreopsis palmata,* wild wormwood—*Artemisia caudata, Artemisia dracunculoides,* prairie sage—*Artemisia frigida,* Hill's thistle—*Cirsium Hillii,* western ragweed, *Ambrosia psilostachya.*

[5] Oak groves— Roesmount to St. Paul. The herbaceous vegetation is comparatively poor in the number of species, yet some of these occur in considerable abundance. The more characteristic plants in spring and early summer are: rue anemone—*Anemonella thalictroides,* wood anemone—*Anemone quinquefolia,* wild crane's-bill—*Geranium maculatum,* false lily-of-the-valley—*Maianthemum canadense,* false Solomon's seal—*Smilacina stellata,* meadow rue—*Thalictrum dioicum,* cream-colored vetchling—*Lathyrus ochroleucus,* shinleaf wintergreen—*Pyrola elliptica,* sessile-leaved bellwort--*Oakesia sessilifolia,* snakeroot—*Sanicula marilandica,* northern bedstraw—*Galium boreale,* wood sorrel- *Oxalis stricta,* hog peanut—*Amphicarpa monoica.*

These are succeeded later by: sunflowers—*Helianthus hirsutus, Helianthus strumosus,* Canada goldenrod—*Solidago canadensis,* early goldenrod—*Solidago juncea,* arrow-leaved aster—*Aster sagittifolius,* common blue wood-aster--*Aster cordifolius,* starved aster—*Aster lateriflorus.*

It is to be noted that from the southern boundary of the state to St. Paul there are no native evergreen trees along the route of the highway. The large specimens which are sometimes seen around old homesteads and in cemeteries were all planted by the early settlers, and the evergreen most commonly seen, the Norway spruce, is not even a native of North America. Indeed Minnesota, south of the Minnesota River, was naturally almost devoid of conifers. Red cedars, around some of the lakes and on the bluffs and some white pines in the broken country towards the Mississippi, were the only fairly common species.

On leaving St. Paul the highway traverses a region of oak groves and sandy prairie, and outposts of the northern coniferous forest are soon encountered in the form of small tamarack swamps. Around White Bear[6] and Bald Eagle lakes there are considerable belts of mixed hardwood forest but northward through Hugo the country is sandy prairie, interspersed with low marshy places. Extensive tamarack swamps can be seen to the west of Hugo.

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[6] Herbaceous vegetation of the White Bear and Hugo region. Immediately north of White Bear village the road for a short distance passes through a patch of timber of the same character as the "Big Woods" with essentially the same type of undergrowth (see footnote No. 3). A short distance farther on the country becomes sandy and the land for the most part is cultivated or pastured so that the native vegetation is comparatively sparse. On embankments along the roadside or along the railroad right-of-way the following species are to be found.

Spring and early summer: pasque flower—*Anemone patens*, bird's-foot violet—*Viola pedata*, arrow-leaved violet—*Viola sagittata*, prairie violet—*Viola pedatifida*, hoary puccoon—*Lithospermum canescens*, hairy puccoon—*Lithospermum Gmelini*, lupine—*Lupinus perennis*, blue-eyed grass—*Sisyrinchium campestre*, lady's-tobacco—*Antennaria plantaginifolia*, purple avens—*Geum triflorum*, large-flowered beard tongue—*Pentstemon grandiflorus*, yellow vetchling—*Lathyrus ochroleucus*, spiderwort—*Tradescantia reflexa*, sheep sorrel—*Rumex acetosella*.

Midsummer flora: northern bedstraw—*Galium boreale*, butterfly weed—*Asclepias tuberosa*, dogbane—*Apocynum androsaemifolium*, purple prairie clover—*Petalostemum purpureum*, figwort—*Scrophularia leporella*, ground cherry—*Physalis lanceolata*, frost weed—*Helianthemum majus*, evening primrose—*Oenothera biennis*, daisy fleabane—*Erigeron ramosus*, bush clover—*Lespedeza capitata*, wild bergamot—*Monarda fistulosa*, giant hyssop—*Agastache foeniculum*.

The following grasses are also conspicuous: beard grass—*Andropogon furcatus*, nodding wild rye—*Elymus canadensis*, Indian grass—*Sorghastrum nutans*, sand dune grass—*Calamovilfa longifolia*, switch grass—*Panicum capillare*.

The following shrubs are also frequent: prairie rose—*Rosa pratincola*, dewberry—*Rubus villosus*, lead plant—*Amorpha canescens*, New Jersey tea—*Ceanothus americanus*, wolfberry—*Symphoricarpos occidentalis*.

Autumn vegetation: common sunflower—*Helianthus annus*, giant sunflower—*Helianthus grosse-serratus*, stiff-haired sunflower—*Helianthus scaberrimus*, oxeye—*Heliopsis scabra*, golden aster—*Chrysopsis villosa*, smooth aster—*Aster laevis*, sky-blue aster—*Aster azureus*, blazing star—*Liatris scariosa*, Canada goldenrod—*Solidago canadensis*, stiff-leaved goldenrod—*Solidago rigida*, showy goldenrod—*Solidago speciosa*, field goldenrod—*Solidago nemoralis*.

Roadside weeds: Throughout this sandy region the most common weeds are: ragweed—*Ambrosia artemisiifolia*, horseweed—*Erigeron canadense*, cocklebur—*Xanthium canadense*, squirreltail grass—*Hordeum jubatum*, knot-grass—*Polygonum aviculare*, sand bur—*Cenchrus tribuloides*, pepper-grass—*Lepedium apetalum*, tumbling mustard—*Sisymbrium altissimum*, cypress spurge—*Euphorbia cyparissias*, Russian thistle—*Salsola Kali*, umbrella wort—*Oxybaphus hirsutus*, carpet weed—*Mollugo verticillata*, spotted spurge—*Euphorbia maculata*, dock—*Rumex mexicanus*, bindweed—*Polygonum Convolvulus*, Canada thistle—*Cirsium arvense*, mullein—*Verbascum thapsus*, butter and eggs—*Linaria vulgaris*, bull thistle—*Cirsium lanceolatum*.

PLATE X

LEAVES OF COMMON MINNESOTA TREES

1. Bur oak. *Quercus macrocarpa.*
2. Yellow birch. *Betula luta.*
3. Black oak. Northern pin oak. *Quercus ellipsoidalis.*
4. White oak. *Quercus alba.*
5. Paper birch. Canoe birch. *Betula papyrifera.*
6. Leaflets of American mountain ash. *Sorbus americana.*

PLATE X

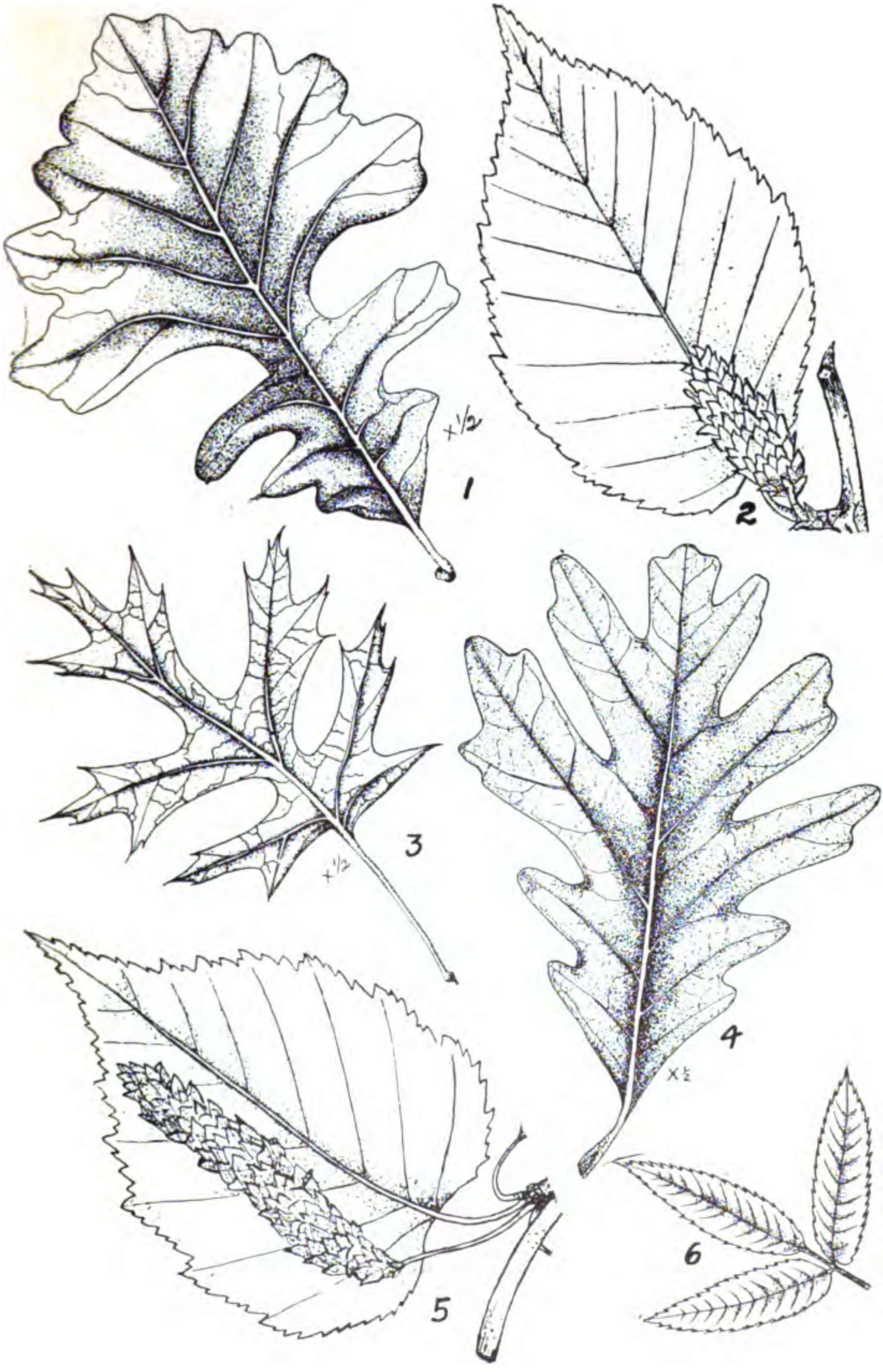
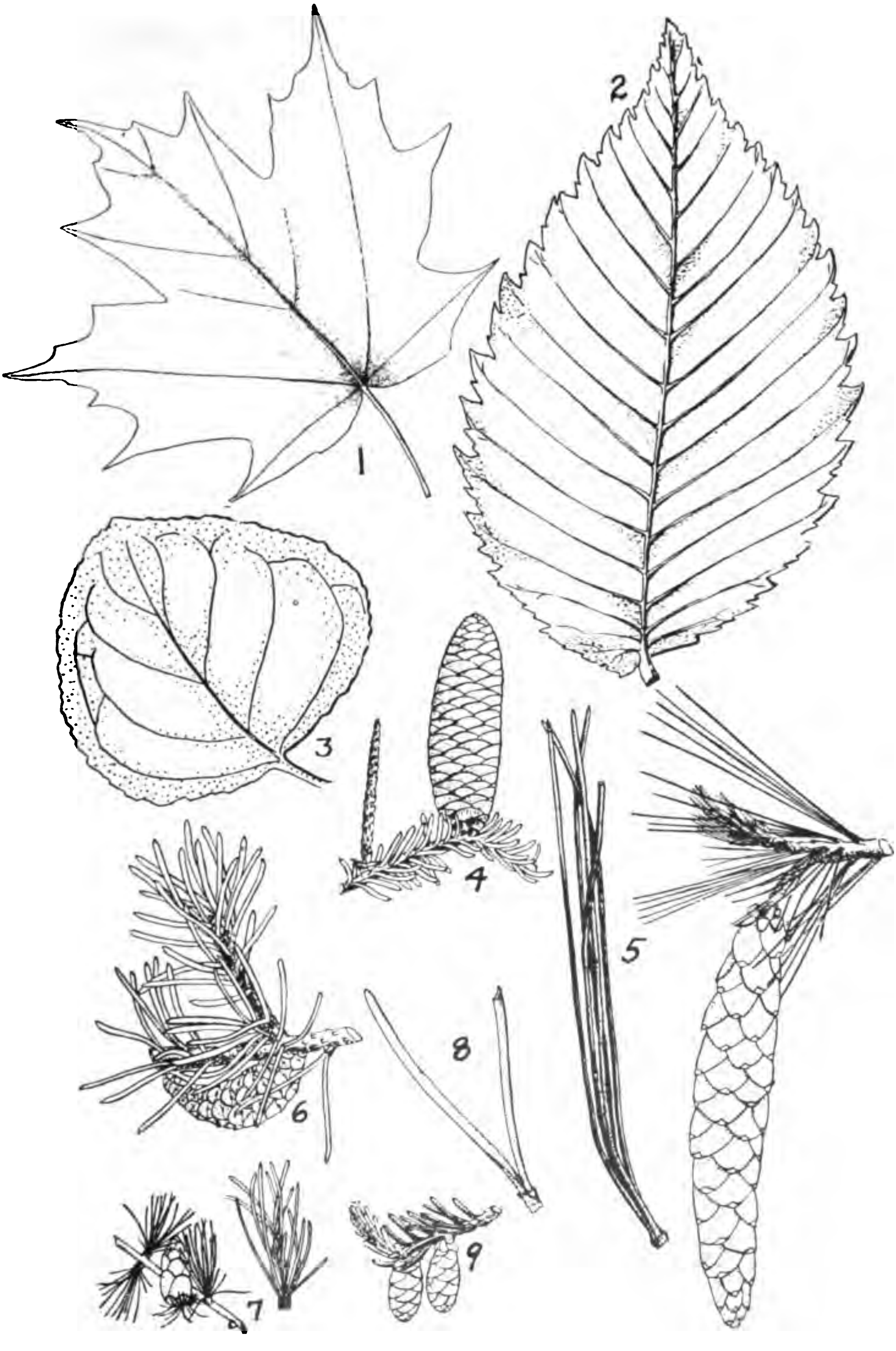


Plate XI

Leaves of Common Minnesota Trees

1. Sugar maple. Hard maple. *Acer saccharum.*
2. White elm. *Ulmus americana.*
3. Aspen. Quaking ash. *Populus tremuloides.*
4. Balsam fir. Balsam. *Abies balsama.*
5. White pine. *Pinus strobus.*
6. Jack pine. *Pinus banksiana.*
7. Tamarack. American larch. *Larix larcina.*
8. Leaf showing two fascicles of the jack pine.
9. Black spruce. *Picea mariana.*

PLATE XI



North of Forest Lake the country becomes more sandy but is here covered[7] with a sparse growth of small scrubby oak. In marked contrast to this rather sterile region is the district of rich soil and heavy forest lying a few miles to the eastward. A short side trip to the Chisago lakes and Taylors Falls takes one very quickly into some of the richest forest and lake land of the state.

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[7] From Forest Lake to Pine City. In the drier situations essentially the same types of herbaceous plants are encountered as farther south. Moist meadows, streams and ponds are more frequent and a different flora inhabits such situations.

Moist meadows. Spring and early summer: marsh marigold—*Caltha palustris*, sweet violet—*Viola pallens*, lance-leaved violet—*Viola lanceolata*, blue meadow violet—*Viola papilionacea*, holy grass—*Hierochloe odorata*, cotton grass—*Eriophorum viridi-carinatum*, meadow parsnip—*Zizia aurea*, painted cup (red and orange colored)—*Castilleja coccinea*, swamp saxifrage—*Saxifraga pennsylvanica*, star grass—*Hypoxis hirsuta*, marsh buttercup—*Ranunculus septentrionalis*.

Midsummer: blue flag—*Iris versicolor*, water hemlock—*Cicuta maculata*, turk's-cap lily—*Lilium superbum*, swamp milkweed—*Asclepias incarnata*, bulbous cress—*Cardamine bulbosa*, yellow water cress—*Radicula palustris*, meadow rue—*Thalictrum dasycarpum*, Canada anemone—*Anemone canadensis*, long-leaved stichwort—*Stellaria longifolia*, persicaria—*Polygonum pennsylvanicum*, great water dock—*Rumex britannica*, marsh cinquefoil—*Potentilla palustris*, purple milkwort—*Polygala sanguinea*, northern willow-herb—*Epilobium adenocaulon*, Virginia goat's-beard—*Krigia amplexicauli*, skullcap—*Scutellaria galericulata*, golden ragwort—*Senecio aureus*, tufted loosestrife—*Lysimachia thyrsiflora*.

The bulk of the vegetation of these meadows is made up of numerous species of sedges *(Carex)*, rushes *(Juncus)*, bulrushes *(Scirpus)*, together with several grasses of which the principal species are fowl meadow grass—*Poa triflora*, nerved manna grass—*Glyceria nervata*, reed meadow grass—*Glyceria grandis*, rough hair-grass—*Agrostis hyemalis*, blue joint—*Calamagrostis canadensis*, marsh muhlenbergia—*Muhlenbergia racemosa*, and reed canary grass—*Phalaris arundinacea*.

Autumn flora: boneset—*Eupatorium perfoliatum*, blazing star—*Liatris pycnostachya*, willow aster—*Aster salicifolius*, panicled aster—*Aster paniculatus*, rush aster—*Aster junceus*, bog goldenrod—*Solidago uliginosa*, late goldenrod—*Solidago serotina*, giant sunflower—*Helianthus giganteus*, bur marigold—*Bidens laevis*, tall tickseed—*Bidens trichosperma*, swamp thistle—*Cirsium muticum*, gerardia—*Gerardia paupercula*, great lobelia—*Lobelia siphilitica*, marsh bell-flower—*Campanula aparanoides*.

Woods: South of Pine City the road crosses the line marking the southern limit of once continuous coniferous forest. Although the original forest has mainly disappeared, many of the herbaceous plants belonging to this type of forest are still to be found throughout the area. Among the more conspicuous upland woods species are: Large flowered wake-robin—*Trillium grandiflorum*, bunchberry—*Cornus canadensis*, yellow Clintonia—*Clintonia borealis*, twisted stalk—*Streptopus longipes*, round-lobed hepatica—*Hepatica americana*, sessile-leaved bellwort—*Oakesia sessilifolia*, wild sarsaparilla—*Aralia nudicaulis*, shinleaf wintergreen—*Pyrola secunda* and *Pyrola elliptica*, twin flower—*Linnaea borealis*, wood strawberry—*Fragaria americana*. The shrubby undergrowth consists mainly of: bush honeysuckle—*Diervilla Lonicera*, blueberry—*Vaccinium pennsylvanicum*, red raspberry—*Rubus strigosus*, beaked hazelnut—*Corylus rostrata*, pin cherry—*Prunus pennsylvanica*, honeysuckle—*Lonicera dioica*, snowberry—*Symphoricarpos racemosus*, June berry—*Amelanchier spicata*, downy arrowood—*Viburnum pubescens*.

Along roadside ditches, borders of moist meadows and in the swamps the characteristic shrubs are: dwarf birch—*Betula pumila*, red osier dogwood—*Cornus stolonifera*, shining willow—*Salix lucida*, pussy willow—*Salix discolor*, slender willow—*Salix petiolaris*, hoary willow—*Salix candida*, hoary alder—*Alnus incana*, high-bush cranberry—*Viburnum americanum*, dwarf alder—*Rhamnus alnifolia*, swamp red currant—*Ribes triste*, northern gooseberry—*Ribes oxyacanthoides*, dwarf raspberry—*Rubus triflorus*, black chokeberry—*Pyrus melanocarpa*, swamp fly honeysuckle—*Lonicera oblongifolia*, Labrador tea—*Ledium groenlandicum*, leatherleaf—*Chamaedaphne calyculata*, swamp laurel—*Kalmia polifolia*, wild rosemary—*Andromeda glaucophylla*, cranberry—*Vaccinium Oxycoccus*, creeping snowberry—*Chiogenes hispidula*.

The interesting herbaceous vegetation of the spruce-tamarack swamps, so characteristic of northeastern Minnesota still persists in the remnants of such swamps which are passed now and then from Hinckley northward towards Duluth. The more striking species of these habitats are: showy lady's slipper—*Cypripedium hirsutum*, mocassin flower—*Cypripedium acaule*, pitcher plant—*Sarracenia purpurea*, sundew—*Drosera rotundifolia*, grass pink—*Callopogon pulchellus*, round-leaved orchis—*Habenaria orbiculata*, rein orchis—*Habenaria hyperborea*, coralroot—*Corallorhiza trifida*, twayblade—*Listera cordata*, yellow Clintonia—*Clintonia borealis*, false lily-of-the-valley—*Maianthemum canadense*, bishop's cap—*Mitella nuda*, goldthread—*Coptis trifolia*, bog wintergreen—*Pyrola uliginosa*, sweet white violet—*Viola incognita*, one-flowered wintergreen—*Moneses uniflora*, star flower—*Trientalis americana*, oak fern—*Dryopteris Linnaeana*, marsh shield fern—*Dryopteris thelypteris*, crested shield fern—*Dryopteris cristata*, cinnamon fern—*Osmunda cinnamomea*.

Beyond Wyoming the same sandy country continues unabated until a few miles south of Pine City, where the heavy clay ridges carry a much finer type of forest. Here first appear large white pines scattered among the deciduous trees. Immediately north of Pine City, however, these signs of the northern woods completely disappear. This region was originally heavy pine forest but the Hinckley fire of 1894 destroyed the forest so completely that there are no remnants of the original vegetation and no more pines are seen until one reaches the Kettle River north of Sandstone. The country not now farmed has grown up to a second growth consisting mainly of aspen, white birch, and some oak interspersed with extensive open swamps or meadows. Owing to the considerable time since the destruction of the original forest much of the second growth has reached larger size than in the more recently burned-over districts further north.

After crossing the Kettle River[8] nine miles north of Sandstone, the highway traverses for a short distance a relatively unburned district which indicates the original type of vegetation of much of this region. Owing to the sandy nature of the country the principal trees are jack pine and Norway pine mingled with white birch and aspen. Along the road are considerable clumps of sweet fern. From here up to Carlton the country has been very extensively and repeatedly burned and the upland is largely covered with second growth of birch and aspen in various stages of development, much of it scarcely more than thickets. Throughout this area there are extensive swamps sometimes filled with tamarack mingled with spruce and fir and sometimes, where the fires have been severe, merely covered with tangled thickets of willows and alders.

At Carlton the climatic influence of Lake Superior begins to be definitely felt, and there are also several changes in the appearance of the vegetation due to the outcropping of hard rock. On the rocky ridges one frequently sees white spruce and white cedar while certain plants characteristic of the Lake Superior region appear in the undergrowth.[9] One of the most conspicuous of these is the flowering raspberry, a shrub with maple-like leaves and large white flowers. The fruit which is bright red and much flatter than the ordinary raspberry is edible but remarkably tasteless. In this vicinity blueberries are also abundant.

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[8] In the vicinity of the Kettle River a flora typical of jack pine forests is encountered. The characteristic shrubby species are: blueberry—*Vaccinium pennsylvanicum*, sweet fern—*Myrica asplenifolia*, trailing arbutus—*Epigaea repens*, wintergreen—*Gaultheria procumbens*, bearberry—*Arctostaphylos Uva-Ursi*, snowberry *Symphoricarpos racemosus*, hairy honeysuckle—*Lonicera hirsuta*, bush honeysuckle—*Diervilla Lonicera*, pipsissewa—*Chimaphila umbellata*.

The most common herbaceous plants are: bunchberry—*Cornus canadensis*, twin flower—*Linnaea borealis*, partridge berry—*Mitchella repens*, lady's tobacco—*Antennaria canadensis*, wood anemone—*Anemone quinquefolia*, large-leaved aster—*Aster macrophyllus*, clubmoss—*Lycopodium calvatum*, bracken fern—*Pteridium aquilinum*, northern bedstraw—*Galium boreale*, cow wheat—*Melampyron lineare*, shinleaf wintergreen—*Pyrola secunda*, mountain rice—*Oryzopsis asperifolia*, oat grass—*Danthonia spicata*.

At the village of Thomson the highway enters the western extremity of Jay Cooke Park which embraces the rugged country of the lower valley of the St. Louis River. A short side trip down through the park reveals a rich and interesting vegetation on account of the great diversity of habitats. Although the chief elements belong to the northern coniferous forest there are a number of species more characteristic of the regions farther south, such as the staghorn sumac, the green ash, the ninebark among woody plants, and tall cinquefoil, alum root, daisy fleabane, and heal-all among the herbs. In the crevices of the rocky ledges grow in great profusion harebell, houstonia, violets, dwarf evening primrose, and the three-toothed cinquefoil. Most of the evergreen trees of the region occur within the park including the three native species of pine, and many kinds of broad-leaved trees are common such as birch, aspen, balsam poplar, alder, ash, and willows.

East of Duluth the influence of Lake Superior is fully felt. In general, vegetation is from a month to six weeks later in developing than it is around the Twin Cities and it has everywhere a very northern aspect. Two species of mountain ash form a conspicuous part of the forest growth with their large clusters of white flowers about July first, and their red berries in autumn. One of the most abundant trees is the white birch which here reaches great size. Of evergreens the white spruce, the jack pine, and the balsam fir are now the most abundant species.[10] All the way from Duluth to the border the greater part of the original forest has been destroyed by fire at one time or another, but portions of the original vegetation are preserved, sometimes in the deep ravines and gorges of streams, sometimes on peninsulas and islands in the lake.[11] Three of the most conspicuous shrubs of this region are the mountain maple, the beaked hazelnut, and Bailey's dogwood. The common red raspberry and the bush honeysuckle are also extremely abundant in all burnt over tracts. After midsummer these same areas are adorned with the showy pink-purple spikes of the fireweed and the red fruit clusters of the bunchberry. Some distance beyond Hovland the highway passes through an extensive muskeg. a peat swamp covered with a shrubby vegetation consisting of plants of the heath family with here and there stunted tamarack and black spruce trees. The chief heaths in this muskeg are Labrador tea and leatherleaf, and in early July, when the former is in blossom, it presents a very beautiful sight. While muskegs are rather rare close to the lake shore they are an exceedingly common feature of the country lying further back beyond the crests of the hills. Thus the roads running from Duluth to the Iron Range pass through an almost continuous stretch of muskegs.

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[9] On the rocky ledges in the vicinity of Thomson and along the St. Louis River in Jay Cooke Park the following species occur frequently: Shrubs: white-flowering raspberry—*Rubus parviflorus*, ninebark—*Physocarpus opulifolius*, blueberry—*Vaccinium pennsylvanicum*, June berry—*Amelanchier spicata*, pin cherry—*Prunus pennsylvanica*, beaked hazelnut—*Corylus rostrata*, green alder—*Alnus crispa*, bush honeysuckle—*Diervilla Lonicera*, red-berried elder—*Sambucus racemosa*, arrowwood—*Viburnum pubescens*, prickly rose—*Rosa acicularis*.

Herbs: pink corydalis—*Corydalis sempervirens*, harebell—*Campanula rotundifolia*, violet—*Viola arenaria*, three-toothed cinquefoil—*Potentilla tridentata*, Houstonia—*Houstonia longifolia*, dwarf evening primrose—*Oenothera pumila*, alum root—*Heuchera hispida*, heal-all—*Prunella vulgaris*, yarrow—*Achillea millefolium*, daisy fleabane—*Erigeron philadelphicus*.

The most abundant and conspicuous plant within the city limits of Duluth, covering vacant lots, the low ground along the harbor, and the rocky slopes to the summits and beyond is the meadow buttercup—*Ranunculus acris*. This plant is naturalized from Europe and thrives exceedingly well in the acid soil and cool air of the locality. The blooming season lasts for many weeks but is at its height in the latter part of June and early July when the slopes are a mass of bright yellow. The ragweeds, both the common and the giant forms occur in vacant lots and along roadsides in many parts of Duluth but do not occur along the north shore.

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[10] The vegetation of the north shore, except for a number of introduced species belongs to the element known in America as the *northeastern coniferous forest*. On account of the uniformly cool climate which obtains throughout the summer a few far northern or arctic species have become established in the immediate vicinity of the lake. Because of the interest which this region has for the traveler a somewhat comprehensive list of the species occurring mostly within sight of the highway is appended.

Trees: white pine—*Pinus Strobus*, Norway pine—*Pinus resinosa*, jack pine—*Pinus Banksiana*, white spruce—*Picea canadensis*, black spruce—*Picea mariana*, white cedar—*Thuja occidentalis*, tamarack—*Larix laricina*, balsam fir—*Abies balsamea*, white birch—*Betula papyrifera*, yellow birch—*Betula lutea*, aspen—*Populus tremuloides*, balsam poplar—*Populus balsamifera*, black ash—*Fraxinus nigra*, green ash—*Fraxinus pennsylvanica*, red maple—*Acer rubrum*, sugar maple—*Acer saccharum* (rare), white elm—*Ulmus americana* (rare).

Shrubs: yew—*Taxus canadensis*, mountain ash—*Sorbus sitchensis*, American mountain ash—*Sorbus americana*, choke cherry—*Prunus virginiana*, pin cherry—*Prunus pennsylvanica*, ninebark—*Physocarpus opulifolius* var. *intermedius*, June berry—*Amelanchier spicata*, *Amelanchier oligocarpa*, white-flowered raspberry—*Rubus perviflorus*, red raspberry—*Rubus strigosus*, prickly rose—*Rosa acicularis*, beaked hazelnut—*Corylus rostrata*, dwarf birch—*Betula pumila*, sweet gale—*Myrica gale*, mountain maple—*Acer spicatum*, pussy willow—*Salix discolor*, Bailey's dogwood—*Cornus Baileyi*, red osier dogwood—*Cornus stolonifera*, Labrador tea—*Ledum groenlandicum*, leatherleaf—*Chamaedaphne calyculata*, blueberry—*Vaccinium pennsylvanicum*, *Vaccinium canadense*, small cranberry—*Vaccinium Oxycoccus*, American cranberry—*Vaccinium macrocarpon*, bush honeysuckle—*Diervilla Lonicera*, hairy honeysuckle—*Lonicera hirsuta*, American fly honeysuckle—*Lonicera canadensis*, speckled alder—*Alnus incana*, green alder—*Alnus crispa*, red-berried elder—*Sambucus racemosa*, squashberry—*Viburnum pauciflorum*, smooth gooseberry—*Ribes oxyacanthoides*, *Ribes saxosum*, swamp black currant—*Ribes lacustre*, swamp red currant—*Ribes triste*, skunk currant—*Ribes prostratum*, northern black currant—*Ribes hudsonianum*.

Herbaceous vegetation. (a) General upland forest: large-leaved aster—*Aster macrophyllus*, yellow Clintonia—*Clintonia borealis*, wild sarsaparilla—*Aralia nudicaulis*, twin flower—*Linnaea borealis*, star flower—*Trientalis americana*, false lily-of-the-valley—*Maianthemum canadense*, bishop's cap—*Mitella nuda*, bunchberry—*Cornus canadensis*, sweet-scented bedstraw—*Galium triflorum*, enchanter's nightshade—*Circaea alpina*, lungwort—*Mertensia paniculata*, club moss—*Lycopodium clavatum*, stiff club moss—*Lycopodium annotinum*, ground pine—*Lycopodium obscurum*, shinleaf—*Pyrola chlorantha*, colt's foot—*Petasites palmata*, spurred gentian—*Halenia deflexa*, wood strawberry—*Fragaria americana*, wood anemone—*Anemone quinquefolia*, dwarf raspberry—*Rubus triflorus*.

(b) On moist shady ledges of river gorges and along stream beds: baneberry—*Actaea rubra*, columbine—*Aquiligea canadensis*, twisted stalk—*Streptopus longipes*, *Streptopus amplexifolius*, blue violet—*Viola cucullaria*, sweet white violet—*Viola pallens*, lady fern—*Athyrium angustum*, brittle fern—*Cystopteris fragilis*, long beech fern—*Dryopteris Phegopteris*, rusty woodsia—*Woodsia illvensis*, bishop's cap—*Mitella nuda*. A number of shade-loving grasses and sedges also occur in these habitats.

(c) On slopes, ridges and generally rocky open situations: fire weed—*Epilobium angustifolium*, everlasting—*Anaphalis margaritacea*, dogbane—*Apocynum androsaemifolium*, fringed black bindweed—*Polygonum cilinode*, blue vetch—*Vicia americana*, figwort—*Scrophularia leporella*, common polypody—*Polypodium vulgare*, yellow wood parsnip—*Zizia cordata*, oat grass—*Danthonia spicata*, June grass—*Poa pratensis*, melic grass—*Melica striata*, strawberry—*Fragaria americana*, bracken fern—*Pteridium aquilinum*, bristly sarsaparilla—*Aralia hispida*.

[11] Rocky Peninsula at Grand Marais. A number of species of infrequent or rare occurrence in Minnesota are found on this rocky point, viz.: mountain cranberry—*Vaccinium Vitis-Idaea*, primrose—*Primula mistassinica*, butterwort—*Pinguicula vulgaris*, false asphodel—*Tofieldia palustris*, shrubby cinquefoil—*Potentilla fruticosa*, three-toothed cinquefoil—*Potentilla tridentata*, tufted bulrush—*Scirpus caespitosus*, sedge—*Carex Halleri*.

As the road ascends on to the high ground towards Mineral Center it enters a strip of exceedingly barren country. The original forest and most of the soil has been entirely destroyed by fire and as yet the only cover is a sparse growth of birch, aspen, pin cherry, jack pine, willows, raspberry bushes, and alders, with a scanty undergrowth of herbaceous plants. Just before reaching Mineral Center a range of low hills covered with heavy forest may be seen to the northward. The forest on these hills is a type very unusual for this part of the state being an almost pure growth of hard maple, with the corresponding undergrowth resembling that found in the deciduous forest farther south. This maple forest has been much used by the Indians as a source of maple sugar. North of Mineral Center extensive cedar-spruce swamps are encountered which for the most part have been untouched by fires. In fact this district up to the international boundary and beyond is either unburned or burned so long ago that the second growth has had opportunity to develop into a respectable forest, and it gives some idea of what all the region from Duluth eastward must once have been.

GLOSSARY

GLOSSARY OF GEOLOGIC TERMS

Agate. A banded or variegated chalcedonic quartz (SiO_2). Usually formed by deposition in layers.

Alluvium. Sediment deposited by streams.

Amygdaloid. A cellular igneous rock, usually formed at the top of a lava flow, whose cavities have been filled with minerals deposited from water solutions; the fillings are called amygdules. Basalt is the most common amygdaloidal rock

Anorthosite. A granular igneous rock composed mainly of labradorite feldspar; closely allied to gabbro and diabase in origin.

Basalt. A dense igneous rock of very dark color, whose fabric is so fine that the grains cannot be perceived with the eye, or, if seen, cannot be recognized. The basalts are of stony, but not of glassy, texture. The color varies from grayish black, greenish, to pure black. Basalts are most often formed by the solidification of lava flows.

Calcite. A common mineral consisting of calcium carbonate ($CaCO_3$). It is the chief constituent of limestone and marble, and is often found in veins and in altered rock. It is usually white to colorless, soft, and has rhombohedral cleavage.

Cleavage. A tendency of a mineral or rock to part along closely spaced parallel surfaces or planes.

Conglomerate. A rock formed from rounded pebbles, usually with more or less sand, mud, etc. A consolidated gravel.

Diabase. A heavy, dark, intrusive rock having the same composition as basalt, but on account of its slower cooling, it has a more crystalline texture. It corresponds closely in origin and composition with gabbro, but differs in texture. The plagioclase crystals are lath shaped and are embedded in olivine and augite.

Dike. A mass of igneous rock that has solidified in a fissure or crack in the earth's crust. Usually applied to a mass that cuts across the beds. (See Sill.)

Dolomite. Similar to limestone, but consists of calcium-magnesium carbonate $[(Ca\ Mg)\ CO_3]$.

Drift (glacial drift). The rock fragments—soil, gravel, and silt—carried by a glacier. Drift includes the unassorted material known as till and deposits made by streams flowing from the glacier.

Extrusive rocks. See Igneous rocks.

Fault. A fracture in the earth's crust accompanied by movement of the rock on one side of the break past that on the other.

Feldspar. Aluminous silicates of potassium, sodium, or calcium. The main varieties are orthoclase, which is a potassium aluminum silicate, and plagioclase, which consists of nearly all possible mixtures of sodium and calcium aluminum silicates. They are the most abundant minerals found in igneous rocks and vary in color from white to red or dark, possess two cleavages, and are hard as steel.

Felsite. A light-colored dense rock composed mainly of feldspar, often with quartz, in which the crystallization is usually imperfect or obscure, giving a close-grained texture with conchoidal fracture and a flinty aspect.

Formation. A rock layer, or series of continuously deposited layers grouped together, regarded by the geologists as a unit for purposes of description and mapping. A formation is usually named from some place where it is exposed in its typical character, for example, St. Peter sandstone.

Fossil. The whole or any part of an animal or plant that has been preserved in the rocks or the impression left by an animal or plant. (See Plate I.) This preservation is invariably accompanied by a change in substance, and from some impressions the original substance has all been removed.

Gabbro. Dark gray to black granular igneous rock consisting chiefly of plagioclase and pyroxene. Gabbros are always formed by solidification of magma beneath the surface and that results in the granular texture. They correspond closely in chemical composition to the basalts and diabases.

Glacier. The moving part of an ice sheet which is formed by the packing of snow on land. The glacier moves forward by forces from within developed chiefly by the weight of the ice.

Granite. A crystalline igneous rock that has solidified slowly deep within the earth. Usually light colored and consists of feldspar, quartz, hornblende or mica, and lesser amounts of other minerals.

Graywacke. Sandstone-like rock of a prevailing gray color which, in addition to quartz and feldspar, contains fragments of many other minerals and rocks.

Ground moraine. All of the drift deposited beneath the advancing ice, and all deposited from the base of the ice when it melts.

Igneous rocks. Rocks formed by the cooling and solidification of a hot liquid material known as magma, that has originated at unknown depths within the earth. Those that have solidified beneath the surface are known as intrusive rocks. Those that have flowed out over the surface are known as effusive rocks, extrusive rocks, or lavas. The term volcanic rocks includes not only lavas, but bombs, pumice, tuff, volcanic ash, and other fragmental material thrown out from volcanoes.

Intrusive rocks. See Igneous rocks.

Joints. Fractures or fissures in rocks along which there has been little or no movement.

Limestone. A sedimentary rock composed of calcium carbonate ($CaCO_3$). Deposited mainly in the ocean by chemical and organic means. The calcium is carried to the ocean in solution in river waters.

Magma. Hot liquid material within the earth which on cooling crystallizes to form igneous rocks. During the cooling certain gases and liquids are probably given off. Those magmas that reach the surface form lavas.

Magnetite. Iron ore, iron oxide (Fe_3O_4), black, heavy, and strongly magnetite. Titaniferous magnetite is magnetite plus more or less ilmenite, and iron-titanium oxide ($FeTiO_3$).

Metamorphism. Any considerable change in rocks effected in the earth by heat, pressure, solutions, or gases. A common cause of the metamorphism is the intrusion into them of igneous rocks. Rocks that have been greatly changed in minerals or texture are termed metamorphic

Outcrop. That part of a rock that appears at the surface. The appearance of a rock at the surface or its projection above the soil.

Outwash plain. The broad sheet of débris spread out in front of a terminal moraine by the numerous streams which flow out from an ice sheet or glacier.

Phenocrysts. The large mineral crystals of a porphyry.

Porphyry. Any igneous rock in which certain crystal constituents are distinctly larger than the other constituents.

Quartz. A common mineral consisting of silica (SiO_2). It is hard, usually colorless, has no cleavage. Ordinarily sand and sandstone as well as quartzite are composed chiefly of this mineral.

Quartzite. A rock composed of sand grains cemented by silica into an extremely hard mass. The bond of the cement is normally so strong that the sand grains split when the rock is broken.

Rhyolite. Those dense igneous rocks of light color which correspond in composition to the granite. The rhyolite corresponds in texture to the basalts. They often form from lava flows but also from intrusions near the surface.

Sandstone. A sedimentary rock composed of grains of sand cemented together usually by silica, calcite, or iron oxide.

Sedimentary rocks. Rocks formed by the accumulation of sediment in water (aqueous deposits) or from air (eolian deposits). The sediment may consist of rock fragments or particles of various sizes (conglomerate, sand stone, shale); of remains or products of animals or plants (certain limestones and coal); of the product of chemical action or evaporation (salt, gypsum, etc.); or of mixtures of these materials. A characteristic feature of sedimentary deposits is a layered structure known as bedding or stratification. Each layer is a bed or stratum. Sedimentary beds as deposited lie flat or nearly flat except when they have been tilted by earth movements.

Shale. A sedimentary rock consisting of hardened thin layers of fine mud.

Sill. A mass of igneous rock intruded or forced between the layers of other rocks.

Slate. A rock that by pressure within the earth has acquired the property of splitting smoothly into thin plates. Slates are usually derived from shales and the cleavage is smoother and more regular than the splitting of schist along its grain.

Stratification. See Sedimentary rocks.

Strike. The direction along which an inclined rock layer would meet the earth's surface if that surface were level. The outcrop of a bed on a plain is coincident with its strike.

Syenite. A granular rock composed chiefly of feldspar and differing from granite mainly in the absence of quartz.

Syncline. An inverted arch or fold of bedded or layered rock. Suggestive in form of a canoe.

Terminal moraine. Thick accumulation of drift made at the end of a glacier or at the edge of an ice sheet, especially where its end or edge remained stationary, or nearly so, for a considerable time.

Terrace. A steplike bench on a hillside. Most terraces along rivers are remnants of valley bottoms formed when the streams flowed at higher levels. Other terraces have been formed by waves. Some terraces have been cut in solid rocks, others have been built up of sand and gravel, and still others have been partly cut and partly built up.

Thomsonite. One of a group of minerals known as the zeolites. It is a complex hydrous aluminum silicate of sodium and calcium. It usually has a radiating structure with variable colors which gives it an attractive pattern when polished. Occurs in cavities in amygdaloidal basalt, especially in the Lake Superior region.

Topography. The configuration of the earth's surface, or of a section of the surface, including its relief, the position of its streams, lakes, roads, cities, and so on.

Trap. A general term for igneous rocks of the darker basaltic type.

Unconformity. A break in the regular succession of sedimentary rocks, indicated by the fact that one bed rests on the eroded surface of one or more beds which may have a distinctly different dip from the bed above. An unconformity may indicate that the beds below it have at some time been raised above the sea, and have been eroded. In some places beds thousands of feet thick have been washed away before the land again became submerged and the first bed above the surface of unconformity was deposited. If beds of rock may be regarded as leaves in a volume of geologic history, an unconformity marks a gap in the record.

Weathering. The group of processes, such as the chemical action of air and rain water and of plants and bacteria, and the mechanical action of changes in temperature, whereby rocks on exposure change in character, decay, and finally crumble into soil.

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